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OUTLINE OF THEORY OF IMPULSE CURRENTS

BY CHARLES P. STEINMETZ

ABSTRACT OF PAPER

In Part I it is shown how, from the integral of the general differential equation of the electric circuit, which has been discussed in a previous paper, all the types of electric currents are derived as special cases, corresponding to particular values of the integration constants.

The equations of the circuits with massed constants, that is, the usual electric circuits, are derived by substituting zero for the (electrical) length of the circuit.

Besides the general transients, discussed in a previous paper, three main classes of currents are shown to exist, corresponding to different values of the time exponent b:

The alternating currents, corresponding to b = imaginary, which are the useful currents of our electric circuits.

The impulse currents, corresponding to real values of b, which may be called harmful currents of our electric circuits.

And, as limit case, for $b = 0$, the continuous-current circuit with distributed constants.

The last case, a continuous current in a circuit with distributed resistance and leakage, is discussed, and it is shown that such continuous-current circuit has many features which are usually considered as typical of alternating-current wave transmission. It consists of a main current and a return current; complete reflection occurs at the end of the circuit; partial reflection at a transition point; a surge resistance exists, which, connected to the circuit, passes the current without reflection.

In Part II an outline of the theory of impulse currents is given. They comprise two classes, the non-periodic and the periodic impulse currents. The equations of both are given in different form, by exponential and by hyperbolic or trigonometric functions. Their characteristics are:

Impulse current and voltage may be resolved into a main wave and a return wave. The return wave is displaced from the main wave in time and in position. A time displacement exists between the two current waves and their corresponding voltage waves. This time displacement may be a lag of the current behind the voltage, or a lead, depending on the circuit constants. In the periodic impulse currents, the displacement between main wave and return wave is represented by a position angle, and the two current waves are in quadrature in position, to their respective voltage waves.

A few special cases are discussed.

I. TYPES OF CURRENT

A. General

If

r = resistance
g = shunted conductance
L = inductance
C = capacity

per unit length of any circuit or section of a circuit, then in any line element dl of the circuit, the voltage consumed is

$$\frac{d\,e}{d\,l} = ri + L\,\frac{di}{dt} \tag{1}$$

and the current consumed is

$$\frac{d\,i}{d\,l} = g\,e + C\,\frac{d\,e}{d\,t} \tag{2}$$

Differentiating (**1**) over dt, and (**2**) over dl, and combining gives

$$\frac{d^2i}{dl^2} = LC\,\frac{d^2i}{dt^2} + (r\,C + g\,L)\,\frac{d\,i}{d\,t} + r\,g\,i \tag{3}$$

Integrating,

$$i = A\,\epsilon^{-al}\,\epsilon^{-bt} \tag{4}$$

$$e = \frac{b\,L - r}{a}\,A\,\epsilon^{-al}\,\epsilon^{-bt} \tag{5}$$

$$= \sqrt{\frac{b\,L - r}{b\,C - g}}\,A\,\epsilon^{-al}\,\epsilon^{-bt}$$

$$= z\,i$$

where

$$z = \sqrt{\frac{b\,L - r}{b\,C - g}} \tag{6}$$

is the *surge impedance* or *natural impedance* of the circuit, and a and b are related by the equation

$$a^2 = b^2 LC - b\ (r\,C + g\,L) + rg \qquad (7)$$

$$= (bL - r)\ (bC - g)$$

The general solution then is a sum of such terms (**4**) and (**5**).

These equations must represent every existing electric circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the alternating-current transmission line to the telephone circuit, with the only limitation, that r, g, L, C are constant within the range of the currents and voltages considered.

The difference between all electric circuits thus merely consists in the difference of the constants A, a and b, and the difference in the length l of the circuit.

If $l = 0$, that is, the length of the circuit is negligible compared with the rate of change of i or e, (**4**) and (**5**) give the equations of all the circuits with massed constants, otherwise we get the equations of the circuits with distributed constants.

In general, a and b are general numbers, related to each other as in (**7**). Choosing b as the independent constant,

b = 0 gives the continuous currents.

b = real gives the impulse currents.

b = imaginary gives the alternating currents.

b = general or complex imaginary gives the general transients.

b = 0 or imaginary thus gives the *permanents*, continuous current and alternating current.

b = real or general gives the *transients*, impulse currents and general transients.

Thus, while the continuous currents represent a limiting case, the alternating currents and the impulse currents are two coordinate classes of currents. While the alternating currents are the useful currents of our electric systems, the impulse currents may be said to be the harmful currents in our systems, as many of the disturbances and troubles in electric systems are caused by them.

The theory of alternating currents is discussed in numerous publications, but little systematic study has been made of the impulse currents, and their general theory thus will be given in the following, and also that of the limiting case of the continuous

currents in a general circuit of distributed constants. The theory of the general transients has been outlined in a previous paper.*

B. Circuits with Massed Constants

Substituting in (**4**) and (**5**):

$$e = 0 \text{ when } l = 0$$

and considering that, by equation (**7**), a can have two values, for every value of b, $+ a$ and $- a$, we have,

$$\begin{aligned} i &= A\, \epsilon^{-bt} \left\{ \epsilon^{-al} + \epsilon^{+al} \right\} \\ e &= \frac{bL - r}{a} A\, \epsilon^{-bt} \left\{ \epsilon^{-al} - \epsilon^{+al} \right\} \end{aligned} \quad (8)$$

Assuming now l as infinitely small, and substituting

$$\epsilon^{\pm al} = 1 \pm a\, l \quad (9)$$

in (**8**), gives, as the general equation of the circuit with massed constants,

$$\begin{aligned} i &= B\, \epsilon^{-bt} \\ e &= (r_0 - bL_0)\, B\, \epsilon^{-bt} \end{aligned} \quad (10)$$

where

$B = 2\,A$

$r_0 = l\,r =$ total resistance of circuit,

$L_0 = l\,L =$ total inductance of circuit.

Substituting $b = 0$ in (**10**), gives

$$\begin{aligned} i &= B \\ e &= r_0\, B \end{aligned} \quad (11)$$

as the equation of the continuous-current circuit.

For $b =$ real (**10**), the equations of the inductive discharges are

$$\begin{aligned} i &= B\, \epsilon^{-bt} \\ e &= (r_0 - bL_0)\, B\, \epsilon^{-bt} \\ &= r_0\, i + L_0 \frac{di}{dt} \end{aligned} \quad (12)$$

*A. I. E. E. Transactions 1908, page 1231, and more completely in Section IV of "Transient Phenomena."

Substituting $b = \pm j\, c$ gives as the equation of the alternating-current circuit,

$$
\begin{aligned}
i &= C_1 \cos ct + C_2 \sin ct \\
e &= (r_0\, C_1 - c\, L_0\, C_2) \cos ct + (r_0\, C_2 + c l_0\, C_1) \sin ct
\end{aligned}
\tag{13}
$$

where

$$
\begin{aligned}
C_1 &= B_1 + B_2 \\
C_2 &= j\,(B_1 - B_2)
\end{aligned}
\tag{14}
$$

C. Continuous-Current Circuit with Distributed Constants

$$b = 0$$

From (7) we have

$$a = \pm \sqrt{rg} \tag{15}$$

and from (6),

$$z = \pm \sqrt{\frac{r}{g}} \tag{16}$$

substituting (15) and (16) in (4) and (5) gives

$$i = A_1\, \epsilon^{-l\sqrt{rg}} + A_2\, \epsilon^{+l\sqrt{rg}} \tag{17}$$

$$e = \sqrt{\frac{r}{g}}\, \{A_1\, \epsilon^{-l\sqrt{rg}} - A_2\, \epsilon^{+l\sqrt{rg}}\} \tag{18}$$

These equations do not contain L and C, that is, inductance and capacity have no effect on the permanent continuous-current circuit with distributed constants, but only resistance and conductance, that is, leakage.

Equations (17) and (18) are the equations of a direct-current circuit having distributed leakage, such as a metallic conductor submerged in water, or the current flow in the armor of a cable laid in the ground, or the current flow in the rail return of the direct-current railway, etc.

r is the series resistance per unit length, g the shunted or leakage conductance per unit length of circuit.

Where the leakage conductance is not uniformly distributed, but varies, the numerical values in (**18**) change wherever the circuit constants change, just as would be the case if the resistance r of the conductor changed. If the leakage conductance g is not uniformly distributed, but localized periodically in space—as at the ties of the railroad track,—when dealing with a sufficient circuit length, the assumption of uniformity would be justified as an approximation.

(*a*) If the conductor is of infinite length—that is, of such great length, that the current which reaches the end of the conductor, is negligible compared with the current entering the conductor, we have

$$A_2 = 0$$

This gives

$$i = A\,\epsilon^{-l\sqrt{rg}}$$

$$e = A\sqrt{\frac{r}{g}}\,\epsilon^{-l\sqrt{rg}} \tag{19}$$

or

$$e = \sqrt{\frac{r}{g}}\,i \tag{20}$$

that is, a conductor of infinite length (or very great length) of series resistance r and shunted conductance g, has the effective resistance $r' = \sqrt{\frac{r}{g}}$.

It is interesting to note, that at a change of r or of g the effective resistance r', and thus the current flowing into the conductor at constant impressed voltage, or the voltage consumed at constant current, changes much less than r or g.

(*b*) If the circuit is open at $l = l_0$, we have

$$i = A_1\,\epsilon^{-l_0\sqrt{rg}} + A_2\,\epsilon^{+l_0\sqrt{rg}} = 0$$

Hence, if

$$A = A_1\,\epsilon^{-l_0\sqrt{rg}} = -A_2\,\epsilon^{+l_0\sqrt{rg}}$$

we have

$$i = A\left\{\epsilon^{+(l_0-l)\sqrt{rg}} - \epsilon^{-(l_0-l)\sqrt{rg}}\right\}$$

$$e = A\sqrt{\frac{r}{g}}\left\{\epsilon^{+(l_0-l)\sqrt{rg}} + \epsilon^{-(l_0-l)\sqrt{rg}}\right\} \tag{21}$$

(*c*) If the circuit is closed upon itself at $l = l_0$, we have

$$e = \sqrt{\frac{r}{g}} \{A_1 \epsilon^{-l_0\sqrt{rg}} - A_2 \epsilon^{+l_0\sqrt{rg}}\} = 0$$

Hence, if

$$A = A_1 \epsilon^{-l_0\sqrt{rg}} = A_2 \epsilon^{+l_0\sqrt{rg}}$$

we have

$$\begin{aligned} i &= A \{\epsilon^{+(l_0-l)\sqrt{rg}} + \epsilon^{-(l_0-l)\sqrt{rg}}\} \\ e &= A\sqrt{\frac{r}{g}} \{\epsilon^{+(l_0-l)\sqrt{rg}} - \epsilon^{-(l_0-l)\sqrt{rg}}\} \end{aligned} \tag{22}$$

If, in (**22**), $l_0 = 0$, that is, the circuit is closed at the starting point, we have

$$i = A \{\epsilon^{-l\sqrt{rg}} + \epsilon^{+l\sqrt{rg}}\}$$

$$e = A\sqrt{\frac{r}{g}} \{\epsilon^{-l\sqrt{rg}} - \epsilon^{+l\sqrt{rg}}\}$$

or, counting the distance in opposite direction, that is, changing the sign of l

$$\begin{aligned} i &= A \{\epsilon^{+l\sqrt{rg}} + \epsilon^{-l\sqrt{rg}}\} \\ e &= A\sqrt{\frac{r}{g}} \{\epsilon^{+l\sqrt{rg}} - \epsilon^{-l\sqrt{rg}}\} \end{aligned} \tag{23}$$

(*d*) If the circuit, at $l = l_0$, is closed by a resistance r_0, we have

$$\left|\frac{e}{i}\right|_{l=l_0} = r_0$$

hence,

$$\frac{A_1 \epsilon^{-l_0\sqrt{rg}} - A_2 \epsilon^{+l_0\sqrt{rg}}}{A_1 \epsilon^{-l_0\sqrt{rg}} + A_2 \epsilon^{+l_0\sqrt{rg}}} = \frac{r_0}{\sqrt{\frac{r}{g}}}$$

$$\frac{A_2\,\epsilon^{+l_0\sqrt{rg}}}{A_1\,\epsilon^{-l_0\sqrt{rg}}} = \frac{\sqrt{\dfrac{r}{g}} - r_0}{\sqrt{\dfrac{r}{g}} + r_0}$$

or,

$$A_2 = A_1\,\epsilon^{-2l_0\sqrt{rg}}\,\frac{\sqrt{\dfrac{r}{g}} - r_0}{\sqrt{\dfrac{r}{g}} + r_0} \tag{24}$$

$$\left.\begin{aligned} i &= A\left\{\epsilon^{-l\sqrt{rg}} - \frac{r_0 - \sqrt{\dfrac{r}{g}}}{r_0 + \sqrt{\dfrac{r}{g}}}\,\epsilon^{-(2l_0-l)\sqrt{rg}}\right\} \\ e &= A\sqrt{\frac{r}{g}}\left\{\epsilon^{-l\sqrt{rg}} + \frac{r_0 - \sqrt{\dfrac{r}{g}}}{r_0 + \sqrt{\dfrac{r}{g}}}\,\epsilon^{-(2l_0-l)\sqrt{rg}}\right\}\end{aligned}\right\} \tag{25}$$

These equations (**23**) and (**25**) can be written in various different forms. They are interesting in showing in a direct-current circuit, features which usually are considered as characteristic of alternating currents, that is, of wave motion.

The first term of (**23**) or (**25**) is the out-flowing or main current or voltage, respectively; the second term is the reflected one.

At the end of the circuit with distributed constants, reflection occurs at the resistance r_0.

If $r_0 > \sqrt{\dfrac{r}{g}}$, the coefficient of the second term is positive, and partial reflection of current occurs, while the return voltage adds itself to the incoming voltage.

If $r_0 < \sqrt{\dfrac{r}{g}}$, reflection of voltage occurs, while the return current adds itself to the incoming current.

If $r_0 = \sqrt{\dfrac{r}{g}}$, the second term vanishes, and the equations (**25**) become those of (**19**), of an infinitely long conductor. That is:

A resistance r_0, equal to the effective resistance (surge impedance) $\sqrt{\frac{r}{g}}$ of a direct-current circuit of distributed constants, passes current and voltage without reflection. A higher resistance r_0 partially reflects the voltage—completely so for $r_0 = \infty$, or open circuit. A lower resistance r_0 partially reflects the current—completely so for $r_0 = 0$, or short circuit.

$\sqrt{\frac{r}{g}}$ thus takes in direct-current circuits the same position as the surge impedance in alternating-current or transient circuits.

D. Alternating-Current Circuits with Distributed Constants

$$b = \pm j\, q$$

by equation (**7**), a then becomes a general number: $\pm\,(h \pm j\, k)$, and the corresponding values of b and a exist:

$$\begin{array}{ll} b = +j\,q, & a = +h - j\,k \\ \quad\;\; -j\,q & \quad\;\; +h + j\,k \\ \quad\;\; -j\,q & \quad\;\; -h - j\,k \\ \quad\;\; +j\,q & \quad\;\; -h + j\,k \end{array}$$

Substituting these in equation (**4**), and substituting for the exponentials with imaginary exponent the trigonometric expression, gives

$$i = \epsilon^{-hl}\,\{B_1 \cos(kl - qt) + B_2 \sin(k\,l - qt)\} + \epsilon^{+hl}\,\{B_3 \cos(kl + qt) + B_4 \sin(k\,l + q\,t)\} \quad (\mathbf{26})$$

where

$$\begin{array}{ll} B_1 = A_1 + A_2 & B_3 = A_3 + A_4 \\ B_2 = j(A_1 - A_2) & B_4 = j(A_3 - A_4) \end{array}$$

Resolving now the trigonometric expression of (**26**) into expressions of single angles, and eliminating the function of time by the introduction of the vector notation,

$$B_1 \cos qt - B_2 \sin qt = B_1 - j\,B_2 = \dot{A}_1.$$

$$B_2 \cos qt + B_1 \sin qt = B_2 + j\,B_1 = j\,\dot{A}_1.$$

$$B_3 \cos qt + B_4 \sin qt = B_3 + j\,B_4 = -\,\dot{A}_2.$$

$$B_4 \cos qt - B_3 \sin qt = B_4 - j\,B_3 = j\,\dot{A}_2.$$

gives as the expression of the current,

$$\dot{I} = \dot{A}_1 \epsilon^{-hl} (\cos kl + j \sin k l) - \dot{A}_2 \epsilon^{+hl} (\cos kl - j \sin kl) \quad (27)$$

and in the same manner, starting with equation (**5**),

$$\dot{E} = \sqrt{\frac{Z}{Y}} \{\dot{A}_1 \epsilon^{-hl} (\cos kl + j \sin kl) + \dot{A}_2 \epsilon^{+hl} (\cos kl - j \sin kl)\} \quad (28)$$

where

$$\begin{aligned} Z &= r + j q L \\ Y &= g + j q C \\ q &= 2 \pi f \end{aligned} \quad (29)$$

These are the usual and well known equations of the alternating-current transmission line in symbolic expressions.

II. IMPULSE CURRENTS

A. General

Impulse currents are characterized by the condition, that the time exponent b in equations (**4**) and (**5**) is real.

By equation (**7**), to every value of b correspond two values of a, equal but of opposite sign:

$$\pm a$$

By the same equation, to every value of a correspond two values of b:

$$b = u \pm s \quad (30)$$

where

$$s = \sqrt{m^2 + \frac{a^2}{L C}} \quad (31)$$

is the *energy transfer constant,*

$$u = \frac{1}{2} \left\{ \frac{r}{L} + \frac{g}{C} \right\} \quad (32)$$

is the *energy dissipation constant,* and

$$m = \frac{1}{2} \left\{ \frac{r}{L} - \frac{g}{C} \right\} \quad (33)$$

is the *distortion constant* of the circuit.

As b must be positive, it must be, by (**30**)

$$s^2 \leqq u^2 \tag{34}$$

Since u and b are real, by (**30**), s must be real, thus by (**31**), $m^2 + \frac{a^2}{L\,C}$ must be real and positive.

As m^2 is real, $\frac{a^2}{L\,C}$ must be real, and must either be positive, or, if negative, $-\frac{a^2}{L\,C}$ must be less than m^2.

a thus must be either real, or imaginary, but it can not be complex imaginary.

This gives two classes of impulse currents:

Non-periodic impulse currents: a real, a^2 positive.

Periodic impulse currents: a imaginary, a^2 negative, and $-a^2 \leqq L\,C\,m^2$

The terms " periodic " and " non-periodic " here refer to the distribution in space, but not in time, since as function of time the impulse currents are always non-periodic.

The relations between the constants thus are:

Non-periodic impulse currents:

$$\begin{aligned} a^2 &= \text{positive} \\ a &= \pm h \\ s &= \sqrt{m^2 + \frac{h^2}{L\,C}} \\ h &= \sqrt{L\,C\,(s^2 - m^2)} \\ u^2 &\geqq s^2 \geqq m^2 \end{aligned} \tag{35}$$

and corresponding values of a and b are:

$$\begin{array}{ll} a: & b: \\ +h & u-s \\ -h & u-s \\ -h & u+s \\ +h & u+s \end{array} \tag{36}$$

Periodic impulse currents:

$$
\begin{aligned}
a^2 &= \text{negative} \\
a &= \pm j\, k \\
s &= \sqrt{m^2 - \frac{k^2}{L\,C}} \\
k &= \sqrt{L\,C\,(m^2 - s^2)} \qquad (37) \\
s^2 &\leqq m^2 \\
k^2 &\leqq m^2\, L\, C
\end{aligned}
$$

and corresponding values of a and b are:

a:	b:
$+jk$	$u - s$
$-jk$	$u - s$
$+jk$	$u + s$
$-jk$	$u + s$

(38)

B. Non-Periodic Impulse Currents

Substituting (**35**) and (**36**) in (**4**) and (**5**), and rearranging, gives:

$$i = \epsilon^{-ut}\,\{A_1\,\epsilon^{-hl+st} + A_2\,\epsilon^{+hl+st} + A_3\,\epsilon^{+hl-st} + A_4\,\epsilon^{-hl-st}\}$$

$$e = \sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left\{c\,A_1\,\epsilon^{-hl+st} - c\,A_2\,\epsilon^{+hl+st} + \frac{1}{c}\,A_3\,\epsilon^{+hl-st} - \frac{1}{c}\,A_4\,\epsilon^{-hl-st}\right\} \qquad (39)$$

where

$$c = \sqrt{\frac{s+m}{s-m}} \qquad (40)$$

These equations (**39**) can be simplified by shifting the zero points of time and distance, by the substitution:

$$
\begin{aligned}
A_1 &= D_1\,\epsilon^{+hl_1 - st_1} \\
A_2 &= D_2\,\epsilon^{-hl_1 - st_1} \\
A_3 &= \pm\, D_1\,\epsilon^{-hl_1+st_1} \qquad (41) \\
A_4 &= \pm\, D_2\,\epsilon^{+hl_1+st_1}
\end{aligned}
$$

$$c = \epsilon^{+st_0} \qquad (42)$$

Hence

$$t_0 = \frac{\log c}{s} = \frac{1}{2\,s} \log \frac{s+m}{s-m} \tag{43}$$

and writing $\qquad t$ for $t - t_1 + t_0$

and $\qquad l$ for $l - l_1$

they then assume the form:

$$\begin{aligned} i &= \epsilon^{-ut} \{D_1 [\epsilon^{-hl+s(t-t_0)} \pm \epsilon^{+hl-s(t-t_0)}] \\ &\qquad - D_2 [\epsilon^{+hl+s(t-t_0)} \pm \epsilon^{-hl-s(t-t_0)}]\} \\ e &= \sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{D_1 [\epsilon^{-hl+st} \pm \epsilon^{+hl-st}] \\ &\qquad + D_2 [\epsilon^{+hl+st} \pm \epsilon^{-hl-st}]\} \end{aligned} \tag{44}$$

or, expressed in hyperbolic functions:

$$\begin{aligned} i &= \epsilon^{-ut} \{B_1 \cosh [hl - st(t - t_0)] - B_2 \cosh [hl + s(t - t_0)]\} \\ e &= \sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{B_1 \cosh [hl - st] + B_2 \cosh (hl + st]\} \end{aligned} \tag{45}$$

or the corresponding sinh functions, in case of the minus sign in equation (**44**).

The impulse thus is the combination of two single impulses of the form

$$\epsilon^{-ut} (\epsilon^{-hl+st} \pm \epsilon^{+hl-st})$$

which move in opposite direction, the D_1 impulse towards rising l: $\frac{dl}{dt} > 0$, and the D_2 impulse towards decreasing l: $\frac{dl}{dt} < 0$.

The voltage impulse differs from the current impulse by the factor $\sqrt{\frac{L}{C}}$ (the "surge impedance"), and by a *time displacement* t_0. That is, in the general impulse, voltage e and the current i are displaced in time.

t_0 thus may be called the time displacement, or time lag of the current impulse behind the voltage impulse.

t_0 is positive, that is, the current *lags* behind the voltage impulse, if in equation (**43**) the log is positive, that is, m is positive, or: $\frac{r}{L} > \frac{g}{C}$, that is, the resistance-inductance term preponderates.

Inversely, t_0 is negative, and the current *leads*, or the voltage impulse lags behind the current impulse, if m is negative, that is, $\frac{r}{L} < \frac{g}{C}$, or the capacity term preponderates.

If $g = 0$, that is, no shunted conductances, the current impulse always lags behind the voltage impulse.

If $m = 0$, that is, $\frac{r}{L} = \frac{g}{C}$, or $\frac{r}{g} = \frac{L}{C}$, $t_0 = 0$, that is, the voltage impulse and the current impulse are in phase with each other, that is, there is no time displacement, and current and voltage impulses have at any time or at any space the same shape; *distortionless circuit.* m therefore is called the *distortion constant* of the circuit.

In the individual impulse

$$\epsilon^{-u}\left(\epsilon^{-hl+st} \pm \epsilon^{+hl-st}\right) = \epsilon^{-hl}\,\epsilon^{-(u-s)t} \pm \epsilon^{+hl}\epsilon^{-(u+s)t} \tag{46}$$

the term ϵ^{-ut} is the attenuation of the impulse by the energy dissipation in the circuit, that is, represents the rate at which the impulse would die out by its energy dissipation.

The first term: $\epsilon^{-(u-s)t}$, dies out at a slower rate than given by the energy dissipation, that is, in this term, at any point l, energy supplied is left behind by the passing impulse, and as the result, this term decreases with increasing distance l, by the factor ϵ^{-hl}; inversely, the second term, $\epsilon^{-(u+s)t}$, dies out more rapidly with the time, than corresponds to the energy losses, that is, at any point l, this term abstracts energy and shifts it along the circuit, and thereby gives an increase of energy in the direction of propagation, by ϵ^{+hl}. In other words, of the two terms of the impulse, the one drops energy while moving along the line, and the other picks it up and carries it along.

The terms $\epsilon^{\pm st}$ thus represent the dropping and picking up of energy with the time, the terms $\epsilon^{\pm hl}$ the dropping and picking up of energy in space along the line. In distinction to u, which

may be called the *energy dissipation constant*, s (and its corresponding h) thus may be called the *energy transfer constant* of the impulse. The higher s is, the greater then is the rate of energy transfer, that is, the steeper the wave front, and s thus may also be called the *wave front constant* of the impulse.

Substituting in equations (**44**), $l = 0$, gives the equation of the impulse in a circuit with massed constants:

$$i = A\,\epsilon^{-ut}\,(\epsilon^{+st} \pm \epsilon^{-st})$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,(\epsilon^{+s(t-t_0)} \pm \epsilon^{-s(t-t_0)})$$

where

$$A = D_1 - D_2$$
$$B = D_1 + D_2.$$

Substituting in equation (**39**),

$$\begin{aligned} A_1 &= \pm B\,\epsilon^{+hl_1 - st_1 + x} \\ A_2 &= \pm B\,\epsilon^{-hl_1 - st_1 - x} \\ A_3 &= \pm B\,\epsilon^{-hl_1 + st_1 + x} \\ A_4 &= \pm B\,\epsilon^{+hl_1 + st_1 - x} \end{aligned} \qquad (47)$$

$$c = \epsilon^{+st_0} \qquad (42)$$

and writing

$$t \text{ for } t - t_1 + t_0 + \frac{x}{s}$$

$$l \text{ for } l - l_1$$

and rearranging, gives

$$\begin{aligned} i &= B\,\epsilon^{-ut}\{\epsilon^{-hl}[\epsilon^{+s(t-t_0)} \pm \epsilon^{-s(t-t_0)}] \pm \epsilon^{+hl}[\epsilon^{+s(t-t_0-t')} \\ &\qquad \pm \epsilon^{-s(t-t_0-t')}]\} \\ e &= B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\{\epsilon^{-hl}[\epsilon^{+st} \pm \epsilon^{-st}] \pm \epsilon^{+hl}[\epsilon^{+s(t-t')} \\ &\qquad \pm \epsilon^{-s(t-t')}]\} \end{aligned} \qquad (48)$$

where

$$t' = \frac{2x}{s} \qquad (49)$$

writing

$$t \text{ for } t - t_1 + t'$$

$$l \text{ for } l - l_1 + \frac{x}{h}$$

the substitution of (**47**) and (**42**), gives, after rearranging,

$$i = B\,\epsilon^{-ut}\left\{\epsilon^{-s\,(t-t_0)}\left[\epsilon^{+hl} \pm \epsilon^{-hl}\right] \pm \epsilon^{+s\,(t-t_0)}\left[\epsilon^{+h\,(l-l')} \pm \epsilon^{-h\,(l-l')}\right]\right\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut}\left\{\epsilon^{-st}\left[\epsilon^{+hl} \pm \epsilon^{-hl}\right] \pm \epsilon^{+st}\left[\epsilon^{+h\,(l-l')} \pm \epsilon^{-h\,(l-l')}\right]\right\} \tag{50}$$

where

$$l' = \frac{2\,x}{h} \tag{51}$$

Equations (**48**) may be interpreted as showing two impulses, the main impulse, and the reflected impulse. The main impulse, with ϵ^{-hl}, decreases with increasing l, that is, progresses towards rising l. The reflected impulse, with ϵ^{+hl}, starts at the time t' after the start of the main impulse, and decreases with decreasing l, that is, progresses towards decreasing l.

The two current impulses lag behind their voltage impulse by time t_0.

Equation (**50**) shows the two component impulses, the first one dropping energy along its path, and thus decreasing with the time at a greater rate than corresponds to the energy dissipation, and the second one, displaced in position from the first one by distance l^1, picking up the energy dropped by the first one.

The current again lags behind the voltage by time t_0.

The distance displacement l^1 of the component impulse in (**50**) is related to the time displacement t' of the two component impulses in (**48**) by (**49**) and (**51**):

$$\frac{l'}{t'} = \frac{s}{h}$$

that is, l' is the distance traveled by the impulse during time t'.

-bolic functions, equations (50) may be written:

$$\epsilon^{-ut} \{ \epsilon^{-s(t-t_0)} \cosh hl \pm \epsilon^{+s(t-t_0)} \cosh h (l - l') \}$$

$$\sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{ \epsilon^{-st} \sinh h\, l \pm \epsilon^{+st} \sinh h (l - l') \} \qquad (52)$$

C. Periodic Impulse Currents

-ting (37) and (38) in (4) and (5), separating the exponentials from the real ones, substituting the -ric expressions for the former, and rearranging, gives

$$\{ \epsilon^{-st} [D_1 \cos kl - D_2 \sin kl] + \epsilon^{+st} [D_3 \cos kl - D_4 \sin kl] \}$$

$$\frac{L}{C}\, \epsilon^{-ut} \{ c\, \epsilon^{+st} [D_2 \cos kl + D_1 \sin kl] + \frac{1}{c}\, \epsilon^{-st} [D_4 \cos kl + D_3 \sin kl] \} \qquad (53)$$

$$c = \sqrt{\frac{m+s}{m-s}} \qquad (54)$$

-ting:

$$\begin{aligned} D_1 &= \pm B\, \epsilon^{-st_1} \cos kl_1 \\ D_2 &= \pm B\, \epsilon^{-st_1} \sin kl_1 \\ D_3 &= \pm B\, \epsilon^{+st_1} \cos k (l_1 - l_0) \\ D_4 &= \pm B\, \epsilon^{+st_1} \sin k (l_1 - l_0) \end{aligned} \qquad (55)$$

$$c = \epsilon^{+sl_0} \qquad (56)$$

$$l_0 = \frac{\log c}{s} = \frac{1}{2s} \log \frac{m+s}{m-s} \qquad (57)$$

-ay:

$$t \text{ for } t - t_1 + t_0$$
$$l \text{ for } l + l_0$$

$$\epsilon^{-ut} \{ \epsilon^{+s(t-t_0)} \cos kl \pm \epsilon^{-s(t-t_0)} \cos k (l - l_0) \}$$

$$= B \sqrt{\frac{L}{C}}\, \epsilon^{-ut} \{ \epsilon^{+st} \sin kl \pm \epsilon^{-st} \sin k (l - l_0) \} \qquad (58)$$

-ging sin and cos in (55), also exchanges sin and cos

Equations (**58**) of the periodic impulse have the same form as equations (**52**) of the non-periodic impulse, except that the trigonometric functions of distance take in the periodic impulse the same position as the hyperbolic function in the non-periodic impulse.

Current and voltage are in quadrature with each other in their distribution in space, in either of the two components of the periodic impulse. That is, in each of the two components maximum current coincides with zero voltage, and inversely.

The two components of the periodic impulse differ in the phase of their space distribution by the distance l_0, the second component lagging behind the first component by the distance l_0.

In each of the two components of the periodic impulse, the current lags behind the voltage by the time t_0.

Current and voltage thus are in quadrature with each other in space, and displaced from each other in time, by the "*time* displacement" t_0.

t_0 is positive, that is, the current lags behind the voltage by time t_0, if m is positive, and t_0 is negative, that is, the current leads the voltage, if m is negative.

Since $m = 1/2\left(\frac{r}{L} - \frac{g}{C}\right)$ it follows:

The current lags behind the voltage, if $\frac{r}{L} > \frac{g}{C}$, that is, if the resistance-inductance effect preponderates.

The current leads the voltage if $\frac{g}{C} > \frac{r}{L}$, that is, if the capacity effect preponderates.

The voltage equals the current times the surge impedance $z = \sqrt{\frac{L}{C}}$, but is in quadrature with it in space, and the current is lagging by t_0 in time.

By the conditions of existence of the periodic impulse, s must numerically be smaller than m.

$$s = 0 \text{ gives}$$

by (**57**): $$s t_0 = 0.$$

by (**37**): $$k = m\sqrt{LC}$$

and by (**58**),

$$i = B\,\epsilon^{-ut}\,\{\cos k\,l' \pm \cos k\,(l' - l_0)\}$$

$$e = B\sqrt{\frac{L}{C}}\,\epsilon^{-ut'}\,\{\sin k\,l' \pm \sin k\,(l' - l_0)\}$$

Hence, current and voltage are in phase in time, but in quadrature in space.

$$s = m \text{ gives}$$

$$k = 0$$

hence, from (**53**),

$$i = \epsilon^{-ut}\,(D_1\,\epsilon^{+mt} + D_3\,\epsilon^{-mt})$$

$$e = \sqrt{\frac{L}{C}}\,\epsilon^{-ut}\,(D_2\,\epsilon^{+m\,(t+t_0)} + D_4\,\epsilon^{-m\,(t+t_0)})$$

hence, substituting for u and m,

$$i = D_1\,\epsilon^{-\frac{g}{C}t} + D_3\,\epsilon^{-\frac{r}{L}t}$$

$$e = \sqrt{\frac{L}{C}}\left\{D_2'\,\epsilon^{-\frac{g}{C}(t+t_0)} + D_4'\,\epsilon^{-\frac{r}{L}(t+t_0)}\right\}.$$

where

$$D_2' = D_2\,\epsilon^{+ut_0}$$

$$D_4' = D_4\,\epsilon^{+ut_0}$$

In this impulse, the capacity terms and the inductance terms are separate, and current and voltage are uniform throughout the entire circuit.

The constants D or A or B are determined, as integration constants, by the terminal conditions of the problem.

For instance, if at the starting moment of the impulse, that is,

at time $t = 0$, the distribution of current and of voltage throughout the circuit are given, we have by (**53**), for $t = 0$,

$$i = \{D_1 + D_3) \cos kl - (D_2 + D_4) \sin kl\}$$

$$e = \sqrt{\frac{L}{C}} \left\{ \left(c D_2 + \frac{D_4}{c} \right) \cos kl + \left(c D_1 + \frac{D_3}{c} \right) \sin kl \right\}$$

The development of the given distribution of current and voltage into a Fourier series thus gives in the coefficients of this series the equations determining the constants D_1, D_2, D_3, D_4.

The expressions for i and e, given in equations (**39**), (**44**), (**45**), (**48**), (**50**) and (**52**) for the non-periodic, and in equations (**53**) and (**58**) for the periodic impulse, obviously apply to a simple impulse only, and a general impulse is represented by the sums $\Sigma\, i$ and $\Sigma\, e$ of all the expressions i and e, whose integration constants satisfy the terminal conditions of the problem.

Discussion on "Outline of Theory of Impulse Currents" (Steinmetz), New York, Jan. 14, 1916.

Charles P. Steinmetz: "Outline of Theory of Impulse Currents" is a continuation of the paper on the general equation of the electric circuit, read eight years ago. In the previous paper it was found that the general differential equation, which applies to every electric circuit or section of circuit having constant values of r, L, g, and C, can be integrated by an expression consisting of four terms, two main waves and their two return waves. One of the waves dies out at a greater, the other at a slower rate than corresponds to the energy dissipation in the circuit, and therefore the former transfers energy to the latter, thus representing the energy transfer along the circuit, as occurring in traveling waves, a-c. transmission etc. These two waves coincide, and the energy transfer coefficient becomes zero, in the stationary oscillation of a uniform circuit; they do not coincide, however, in the stationary oscillation of a compound circuit, but energy transfer occurs from sections of lower energy dissipation, to sections of higher energy dissipation.

In the first part of the present paper, a classification of the different types of electric current is made from the general equation of the electric circuit, and in the second part, various forms of the equations of the general impulse currents are derived.

Two methods of studying engineering phenomena exist, which may be denoted respectively as the *synthetic* method and the *analytic* method.

The synthetic method starts with the study of special cases, and by correlation of the special cases, by generalization and classification progresses from special to general, and thus finally to the complete structure of the engineering science.

The analytic method starts from the general (differential) equation of the science based on the fundamental underlying laws, and by substituting all the possible values of the constants and the terminal conditions, thereby derives the different classes of the phenomena, thus progressing from the most general to the special.

As engineering is based on experience, and experiment necessarily deals with special cases, the synthetic method is the first in the development of engineering, and the analytic method, requiring the knowledge of the fundamental laws, can be attempted only later.

However, the synthetic method can never give assurance of the completeness of our knowledge, for entire classes of phenomena may be omitted, if it happens that they have never been empirically observed or recognized. Inversely, the analytic method gives the complete structure, but only so far as it is based on the fundamental laws represented by

the general equation, and thus may not be comprehensive, since any phenomenon which does not obey these laws, would not be included.

Thus the two methods are supplementary, the analytic method checking the completeness of the synthetic, and the synthetic checking the comprehensiveness of the analytic.

The theory of electrical engineering, relating to direct currents, alternating currents, exponential discharges, oscillating currents and other transients, was developed synthetically; and the purpose of the first part of the present paper is, by the analytic method, to derive all possible types of currents by substituting all possible values of constants and of terminal conditions, and thereby check, whether any class of current of industrial importance has escaped recognition. This appears probable, as the observed transmission line phenomena do not entirely agree with the characteristics of the currents by which they are usually explained.

During the development of high-voltage long-distance transmission, phenomena were observed during disturbances in the transmission lines or underground cables, which could not be explained by the normal voltage supplied by the generating machinery. The first attempt at explanation was made in the study of the "natural period" of the circuit, the abnormal voltages resulting from the free oscillation of the line as a quarter wave (or half wave or full wave), and its higher harmonics. In a few instances this agreed fairly well with the facts, thus pointing to quarter-wave oscillations as possible line disturbances. Usually, however, it did not agree for a quarter wave oscillation would be felt over the entire circuit, whereas experience showed most line disturbances were more local in character, that is, very severe at some places, but rapidly decreasing with the distance. It further showed, as characteristic, the piling up of voltage locally, especially at inductive parts of the circuit, such as transformer end turns, inductances, current transformers etc. This led to the explanation of the disturbance as due to high frequency. High-frequency travelling waves would give local abnormal voltage, and rapid attenuation with the distance from the origin, and therefore would satisfactorily explain the most frequent line disturbances, except in one feature, namely, that such high-frequency oscillating currents should give pronounced resonance effects. Such resonance effects, leading to the formation of stationary oscillations of destructive value, have been observed and experimentally reproduced in recent years, in the high-potential windings of high-voltage power transformers, usually of frequencies between 10,000 and 100,000 cycles, and their existence has therefore been proved. However, in most cases of transmission line disturbances, resonance phenomena are remarkably weak or entirely absent, and it therefore appears that many transmission line disturbances are impulsive rather than oscillatory, which has led to the question of the existence, the characteristics and the equations of impulse currents.

In a circuit with localized capacity, inductance and resistance, the current is either oscillatory or impulsive, depending on the circuit constants, and more particularly the relation of the resistance to the inductance and capacity. In a circuit with distributed constants, however, there is no critical value of constants, that divides the oscillatory and the impulsive phenomena, but, as was shown in the paper of 1908, with the same circuit constants, the phenomena may be oscillatory or they may be impulsive, depending on the terminal conditions, that is, on the cause of the phenomena. Thus oscillating currents as well as impulse currents may exist in the same circuit, although experience seems to show, that at least in long distance transmission lines the latter are rather the more frequent.

To get their relation to the other and better known classes of current, was the purpose of the first part of the present paper.

1. Terminal conditions. The foremost terminal condition is the length l of the circuit. This may be either zero, or finite, or infinite. Substituting $l = 0$ gives the equation of circuits with massed constants: the usual a-c. or d-c. circuits of our systems and apparatus, etc. l = finite gives the equation of circuits with distributed constants and $l = \infty$ gives the case where the circuit is so long, that the disturbance has decreased to a negligible value before reaching the end of the circuit, and thus the reflected disturbance is inappreciable.

2. Constants. The general integral equation of the electric circuit appears as an exponential function, with the time and the distance in the exponent. It thus has a coefficient of the time exponent, b, and a coefficient of the distance exponent, a. a and b are related by a quadratic equation, thus only one is independent, b has been chosen as the independent coefficient. b is a general (or complex imaginary) number, and the two main special cases thus are, (a) where the real term of b is zero, (b) where the imaginary term is zero. (a) gives the alternating currents. (b) gives a non-periodic class of transient currents, which may be called the *impulse currents*. The impulse currents thus appear as a class of currents, as general as, and coordinate with the alternating currents, the latter representing the useful currents of our transmission systems, the impulse currents the foremost type of harmful currents.

The second part of the present paper contains a further classification of the impulse currents, by their distribution along the circuit, as non-periodic and periodic in space, and a derivation of various forms of the equations of the two classes of impulse currents.

Physically, impulse currents, by the steepness of their wave front, give the local piling up of voltage, characteristic of most line disturbances, but as non-periodic currents, they could give resonance phenomena only by multiple reflection, and thus resonance phenomena with impulse currents would be little pronounced or absent.

It appears, therefore, that the most frequent disturbances of our transmission systems show the characteristics of the impulse currents rather than those of oscillating currents, and the study of impulse currents becomes of far greater importance than heretofore assumed.

Thus, the analytic study led to the recognition of the impulse currents as a class of currents, which, while not unknown before, but repeatedly mentioned and discussed, apparently has not sufficiently been realized in respect to its industrial importance.

The reverse operation would now be of interest: to check by the synthetic method, the completeness of the analytic structure, that is, to see to what extent existing or at least industrially important classes of currents are not contained within the scope of the general equation based on constancy of r, L, g and C.

Phenomena are known, which are outside of this equation. Such phenomena are the cumulative oscillations, such as are produced under certain conditions by an arc (not the phenomena of the so-called 'arcing ground;' these are recurrent oscillating discharges), the surging of synchronous machines, the phenomena in circuits operating above corona voltage, etc.

Thus the general equation of the electric circuit, which is the starting point of the present paper and the previous paper, is not all comprehensive, but a still more general analytical investigation is desirable, in which r, L, g and C are not constant, but depend on $\frac{di}{dt}$ and $\frac{de}{dt}$ or an integrated value thereof, as the frequency, etc. Our knowledge of these phenomena is not yet sufficient to attempt an analytic treatment, but more knowledge will have to be acquired by the synthetic method of investigating special classes of phenomena, in a way similar to that attempted with the surging of synchronous machines in the paper on "Instability of Electric Circuits" read before the Chicago Section in 1912.

M. I. Pupin: If I understand Dr. Steinmetz, the object of his paper is to call your attention to a distinct class of electric currents, a class of electric currents which he calls impulse currents and which, he says, has not received as much attention as the direct current and the alternating current. When I saw the notice of the paper and observed the title "Outline of Theory of Impulse Currents," it attracted me very much, because I have always been interested in impulse currents. To me the direct current and the alternating current were simply cases of the more general impulse current.

When Dr. Steinmetz says that equations (**4**) and (**5**) "must represent every existing electric circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the a-c. transmission line to the telephone

circuit, with the only limitation, that r, g, L, C are constant within the range of the currents and voltage considered," he should not be misunderstood in his statement, and I believe that he might be misunderstood. I wish to warn you not to misunderstand that statement, because if you do, you might think that after you read this article you need not read anything else on this subject, so, therefore, I want to warn you against that.

Here Dr. Steinmetz considers the general problem on a long line having distributed inductance, resistance and capacity, and he gives you that, starting from a differential equation. What do we mean by differential equations in electricity? We mean simply this—an equation expressing the various relations between the reactions in a conductor. For instance, take the first equation Dr. Steinmetz gives, which looks so mathematical—as a matter of fact it is nothing more nor less than the expression that in any element of conductor the sum of the electrical actions is equal to the sum of the electrical reactions. That is what he says, and that is Newton's third law of motion, that the sum of action is equal to the sum of reactions in every system of bodies.

Dr. Steinmetz says—Suppose there is that relation between these various electrical reactions and various electrical actions, then the following must be the relation between the current and e.m.f. in any part of the circuit. That is what is called the integral of it. From the equation of reactions you get an expression of the current and the e.m.f., and that is called the integral. That is true for any point of the wire which has certain constants.

Now, when you come to another point of the wire where other constants are, then you have to get another expression for the currents, and since you have an infinite number of points, you may have an infinite number of different expressions for the current, and it is necessary to add these different currents and make them conform to the so-called boundary conditions. As soon as you pass from one element of the wire with certain constants, to another element of the wire with another set of constants, you have to pass through that boundary.

The most difficult thing in mathematical analyses of electrical phenomena is that question of the boundary conditions. So that when Dr. Steinmetz says "These equations must represent every existing electric circuit," he does not mean to say that he has given you a complete solution—he means to say that he has given you a complete solution for any part of the electric circuit, but if you want to have a complete solution, good for any part and for the complete circuit, you have to take this part, and this part, and this part and build it up. That explains the point I had in mind.

It is true that there are problems in electrical engineering which have not been discussed at all, and Dr. Steinmetz has

referred to one of those problems which has interested me for years, the problem of the oscillating arc. It may be that in some oscillating arcs the oscillation is due to the variable resistance. It may be. But the electrical oscillation that takes place in a vacuum tube, such as the pliotron tube, is not due to variable resistance, but is due to something else. That is to say, the oscillating arc acts in a very similar manner to the oscillations produced by an induction motor when you drive it beyond synchronism. Take a single-phase induction motor, drive it beyond synchronism, and provide it with a suitable capacity, and you can get oscillations exactly the same as you do in an oscillating wire in the pliotron tube—there is no variable resistance, there is no variable capacity, there is no variable inductance, the only thing that is variable is the mutual inductance between the primary and secondary circuit.

Dr. Steinmetz to my knowledge has not attempted yet to proceed analytically and pursue this elusive induction motor to see what it will do under certain conditions, but undoubtedly he will, and when he does he will find that an induction motor, whether it is single-phase or polyphase, when supplied with proper capacity and constructed suitably can generate these oscillations in just the same way as the pliotron tube or the oscillating arc. Moreover, if he does not take the proper precaution, the oscillations stored in an induction motor of that kind will be oscillations, not with a negative exponent, but with a positive exponent; that is to say, the oscillations will go on increasing indefinitely until his machine is smashed. The machine has to obey the integral of that differential equation, that is to say, the machine has to obey the law of the electrical reactions. The mechanical power that drives the motor acts, the motor reacts, and the result of that action and reaction is continually piling up energy which appears as magnetic energy, and when the current is big enough, of course, your machine will be either smashed, or the pole pieces will be crushed on to the armature and the machine will come to a standstill.

Harold Pender: Dr. Steinmetz has given us an interesting mathematical discussion of an important class of electric phenomena. It is not difficult to see the physical meaning of the mathematical symbols used in the differential equations given in the paper, but this is not true of many of the symbols appearing in the integral equations. For example, on the last page of the paper there are certain constants enumerated, namely, D_1, D_2, D_3, D_4. What are they? In mathematical language they are called integration constants, and physically they have a definite relation to the physical conditions intially imposed on the circuit, *i.e.*, they depend upon the voltage and current initially established at each point of the circuit. But how may these constants be evaluated in terms of these initial conditions? I hope that Dr. Steinmetz will give us at some future

time a discussion not only of the *qualitative* meaning of these constants, which is not difficult to see, but also their *quantitative* values for various initial conditions which may occur in practise.

The differential equation (**3**) in this paper is one that contains, as Dr. Steinmetz has said, a complete solution of single-circuit lines. By a single-circuit line I mean a circuit which does not contain mutual inductance. If there is mutual inductance a second equation is necessary, and the evaluation of the exponents in the various integral relations requires the solution of a cubic equation instead of a quadratic. When there is mutual inductance between the given circuit and more than one other circuit, the evaluation of the exponents requires the solution of an equation of still higher degree. I give this merely to emphasize the fact that the relations given in the paper apply only to a single circuit which is not influenced by any neighboring circuit, a condition which seldom obtains in any transmission system.

Hans Lippelt: The paper, after introducing equations (**1**) and (**2**), puts forward the following statement:

"These equations must represent every existing electric

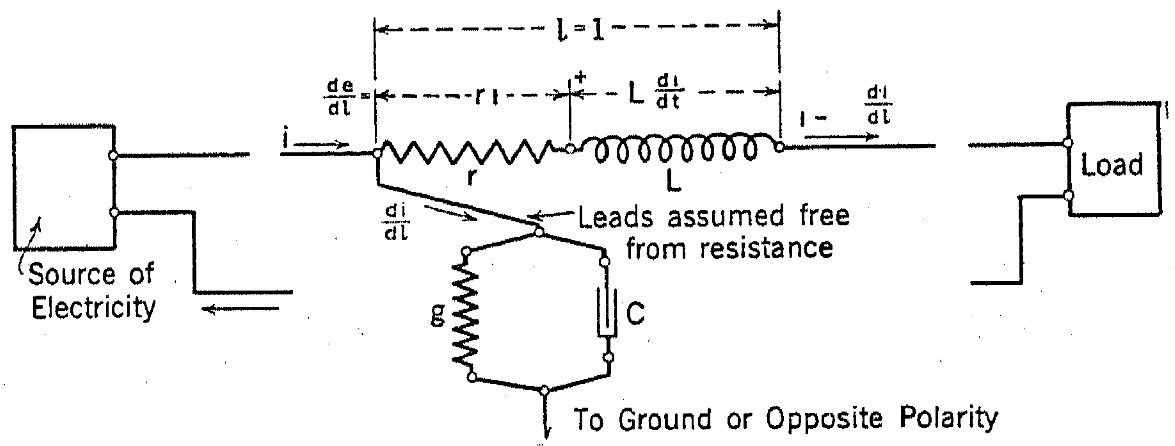


FIG. 1

circuit, and every circuit which can be imagined, from the lightning discharge to the house bell, and from the a-c. transmission line to the telephone circuit, with the only limitation, that r, g, L, C are constant within the range of the currents and voltages considered."

By a peculiar coincidence, it occurred to me that these equations might not include all cases which are situated between the limits given in that statement. As a matter of fact, Dr. Steinmetz in concluding the presentation of the paper tonight mentioned several cases which are not included in these equations. He limited himself, however, again by saying that the cited cases involve variations of the "constants."

To me it seems that there is still another possibility of an electric circuit, which is not covered by equations (**1**) and (**2**). The circuit I have in mind contains capacity in series connection.

Fig. 1 shows in a general way an elementary circuit to which Dr. Steinmetz's equations (**1**) and (**2**) have reference. The figure will be readily understood by observing the notations used

in the paper. The whole circuit is composed of a series of such elementary circuits.

If we have a capacity C_1 in series with the circuit, the latter may be represented as shown in Fig. 2. It is not feasible, however, to assume capacity in each elementary circuit, because the capacity of the total circuit would then be so small that no current at all could flow. The new fundamental equation should, therefore, not refer to the change of voltage per unit length of line $\left(\frac{de}{dl}\right)$, but to a voltage drop in a circuit with massed constants. The length of circuit as such does then not enter into the computation.

If e, the consumed voltage, and the other quantities r_1, r_2, L_1, L_2, C_1, C_2, g, refer to the circuit as per Fig. 2, we have

$$e = r_1 i_1 + L_1 \frac{di_1}{dt} + \frac{1}{C_1} \int i_1 \, dt \tag{1}$$

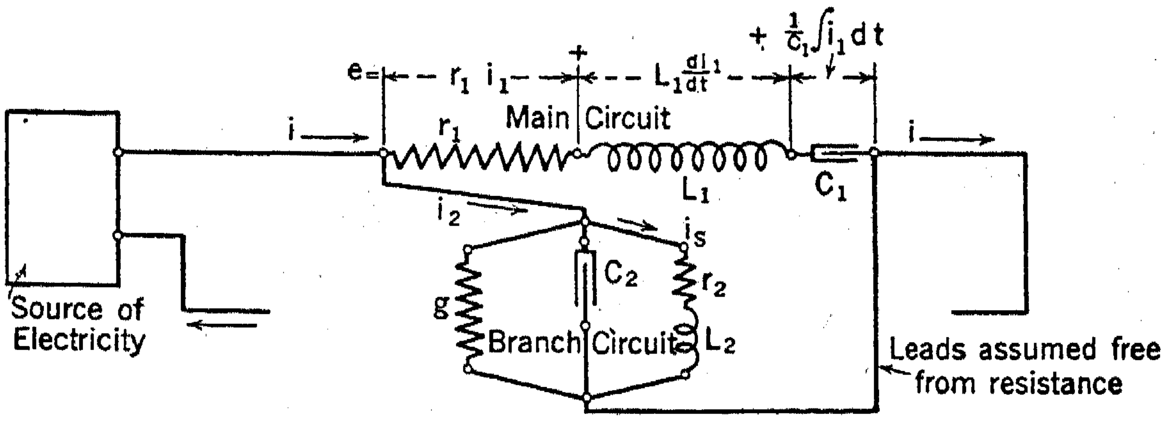


FIG. 2

Similarly, the current diverted from main circuit is, allowing also for self-induction L_2 combined with resistance r_2,

$$i_2 = ge + C_2 \frac{de}{dt} + i_k \times \epsilon^{-\frac{r_2}{L_2}t} + \frac{\epsilon^{-\frac{r_2}{L_2}t}}{r_2} \int e \, d\, \epsilon^{+\frac{r_2}{L_2}t} \tag{2}$$

wherein i_k is defined by the following:

for $t = 0$ $\quad \begin{cases} i_s = i_0 \\ e = e_0 \end{cases}$

$$i_k = i_0 - \frac{e_0}{r_2} + \frac{1}{r_2} \int\limits_{\substack{t=0 \\ \text{const.}=0}} \epsilon^{+\frac{r_2}{L_2}t} \, de$$

finally

$$i = i_1 + i_2 \tag{3}$$

To solve equations (**1**) and (**2**) requires the knowledge of e as a function of the time, and in this respect these equations differ materially from equations (**1**) and (**2**) of the paper. The latter refer to gradients of quantities $\left(\frac{de}{dl} \text{ and } \frac{di}{dl}\right)$, which are independent of actual values of e and i. Equations (**1**) and (**2**) refer to the quantities e and i directly, of which e is equal to the impressed voltage, which governs the whole process, viz., the vector sum of all secondary e.m.fs. must equal e. In the case of Fig. 1, forming only a small part of a large circuit, this partial circuit may draw stored power from adjacent circuits, involving an adjustment of its terminal voltage, and therefore equations (**1**) and (**2**) of the paper must leave this possibility open, which they do.

A partial, or rather advanced solution of equation (**1**) is given in equation (**4**).

$$i_1 = \frac{\epsilon^{\lambda_1 t}}{L_1 (\lambda_1 - \lambda_2)} \left\{ \int \epsilon^{-\lambda_1 t} \, de + K_1 \right\} - \frac{\epsilon^{\lambda_2 t}}{L_1 (\lambda_1 - \lambda_2)} \left\{ \int \epsilon^{-\lambda_2 t} \, de + K_2 \right\} \tag{4}$$

with

$$\lambda_1 = -\frac{r_1}{2L_1} + \sqrt{\frac{r_1^2}{4L_1^2} - \frac{1}{C_1 L_1}}$$

$$\lambda_2 = -\frac{r_1}{2L_1} - \sqrt{\frac{r_1^2}{4 L_1^2} - \frac{1}{C_1 L_1}}$$

K_1 and K_2 = integrating constants.

The last two terms on the right-hand side of equation (**2**) represent the current flowing through the branch loaded with inductance L_2 and resistance r_2, Fig. 2. These terms have been found by treating this branch separately.

To complete the solution of equation (**2**) requires only the substitution of the supposedly known value of e (as a function of time) and carrying out a simple mathematical process.

An application of a circuit with capacity is found in high-voltage d-c. machines, having armature windings of the open coil type. Such machines work entirely with impulse currents and it appears that circuits as per Fig. 2, or similar, will meet the requirements for sparkless commutation of current in the windings.

A. E. Kennelly (by letter): The great advantages of the analytical method set forth in Dr. Steinmetz's valuable paper are:

(1) The integral or primitive equations for all voltage and current waves over conductors are reduced to their simplest fundamental elements.

(2) These equations (**4**) and (**5**) of the paper permit of a new classification of all such voltage and current waves.

When b contains a real component, the paper shows that the wave to which it pertains must speedily disappear. Only when b has no real component can the wave to which it pertains belong to a permanent regime.

There are three cases involving real components of b; namely,

b complex, representing oscillatory transients (1)

b real $\begin{cases} \text{with } a \text{ real, representing non-oscillatory transients} & (2) \\ \text{with } a \text{ imaginary, representing non-oscillatory transients.} & (3) \end{cases}$

The paper distinguishes the two last types by the terms "non-periodic" and "periodic" impulses respectively. But these terms seem to be unsuitable because they suggest recurrence in time; whereas the property in question is a recurrence in distance or space. Would it not therefore be more appropriate to coin the terms "*non-spacic*" and "*spacic*" for this differentiation?

In any case, although the oscillatory and non-oscillatory transients should clearly be distinguished and placed in separate categories, it seems doubtful whether there is enough distinction between the two classes (2) and (3) of the non-oscillatory transients to make their separation important. The paper shows that the only essential difference between these two types is that where a circular distance-angle occurs with the one, a hyperbolic distance-angle occurs correspondingly with the other. Thus both are included in the same generalized trigonometric relations and it remains to be shown whether the differences between them are otherwise great enough to call for separate discussion.

It is perhaps going too far to say that all impulses with real b exponential time-factors are harmful; although the generalization may at present be applied to light and power circuits. In some signaling circuits, as in some submarine cable circuits, such impulses discharging back to ground at the sending end are usefully employed in certain signaling systems.

Charles P. Steinmetz: In regard to the general equation, which I gave in my paper eight years ago, naturally I did not mean that this equation is a final solution of every phenomenon; if I did, I would not have had any reason to write this paper. What I mean to say is that from this equation can be derived the equations of any circuit which fulfills the condition that every one of these four constants r, g, L and C is constant. Where one is variable, whether resistance, or inductance, or the capacity

or conductance, then this general equation does not apply. I mentioned, as an illustration, a couple of circuits where the constants are variable. The transmission line, when operated above corona voltage, also gives a periodically variable conductance.

I referred to the oscillating arc. There I referred to the variable resistance. In the arc it is really a variable effective resistance, as I may call it, defining, as I have done here, resistance as the coefficient of energy dissipation proportionate to the current. The induction machine driven above synchronism also produces oscillations. These oscillations produced by the induction machine when driven above synchronism were discussed in my paper on "Induction Motors" 19 years ago, and their characteris- curves calculated. In the chapter on the "Induction Generator" in "Alternating Current Phenomena," a full discussion is found on the conditions under which an induction machine above synchronism excites, of the maximum voltage and current values to which it may build up, and its dependency on the constants of the external circuit. It may be interesting to note that two such induction generators of 10,000 kw. each, have been in operation for years in the Interborough Rapid Transit station in New York City, as generators producing power.

These impulse currents are a special class of transients. Inasmuch as they are a sub-class of the general transient, they are included in the general equation of my previous paper, but they were not specifically treated.

They apply to a circuit, or a section of the circuit, of uniform constants, but the case which Prof. Pupin discussed, where the circuit constants change, is treated in general in my previous paper under the term "Complex Circuits." It is more particularly treated in that section in my book on "Transient Phenomena," which discusses the transition points between different circuit sections of different constants, as lines, transformers, etc. It is very interesting to note the effect on such a circuit of the transients existing; there is an energy exchange between the different circuit sections, the energy being dissipated in some sections at a rate higher than the average, and in other sections at a rate lower than the average,—there is energy transferred, taken from one section and delivered at another section.

With regard to mutally inductive circuits, even these may be considered under the general equation, by suitable terminal conditions, and effective values of r, g, L, C.

I may say that the circuit as described by Mr. Lippelt is in industrial existence. It is the circuit of the multi-gap lightning arrester.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA

BY A. G. CHRISTIE

ABSTRACT OF PAPER

The paper discusses a number of public utilities in various cities in Western Canada where practically all public utilities are municipally owned and operated. The characteristics of these cities are reviewed and a brief outline of equipments of the various plants is given. The costs and methods of financing these utilities are discussed at considerable length and the charges for various services are summarized. While the paper is not to be regarded as an endorsement of public ownership, the author finds that these utilities on the whole have been conservatively managed and have been practically free from political influence.

WHEN municipally-owned public utilities are discussed in the United States, it is generally held that these are open to the following criticisms:

1. The plant is not kept modern and up-to-date, resulting in indifferent service.

2. Rates are high in consequence of the preceding conditions.

3. The utility's finances are often poorly managed and frequently mixed with other city accounts.

4. The organization is indifferent and without definite lines of authority.

5. Politics are usually a factor in both organization and operation.

Mr. Halford Erickson of the Railroad Commission of Wisconsin has expressed very concisely the American point of view in regard to municipally-owned utilities, in a paper on "State and Local Regulation," an extract of which follows:

"Such utilities furnish no better service than privately owned or operated utilities. In fact, it is often a great deal worse. Municipalities are as a rule slow in responding to new discoveries and improved methods and they often fail to properly list and supervise their meters and other equipment. Examination of the inspector's reports, at least in our state, reveals the fact that while some municipalities provide good service, the service in a greater proportion of them is, on the whole, on a lower level than is the case of privately-operated plants.

"When it comes to rates the situation for municipally-operated utilities is no better. When the Commission first entered upon its duties, it found the state literally streaked with unjust discriminations which were as flagrant in municipally-operated as in privately-operated plants. While these discriminations have now been largely done away with, the task of wiping them out was also fully as great for the former class of plants as for the latter. The same is also true when it comes to establishing and maintaining equitable rates. While the rates charged by the municipally-operated plants are often relatively low, this is not often due to a low cost of production of the service, but largely because in one way or another upkeep and other costs are shifted from the consumer as such to the taxpayer as such."

Practically all public utilities in the cities of the Western Canadian provinces are municipally owned and operated. An investigation into the municipal activities of the cities of this section to determine to what extent the above criticisms in reference to public ownership could be applied to them, should aid materially in presenting new facts in the discussion of public ownership. After a study extending over four years, an inquiry was made during the summer of 1915 into the municipally-owned electric light and power utilities of these cities.

The electric light and power utility was chosen because it was one of the first to be established and is also one with which comparisons can be made with privately owned systems. It has become better organized and established than some of the other civic undertakings and the early mistakes in its management are now apparent. Its organization is also more extensive than later utilities. Hence for the reasons just stated, its production costs and physical equipment would probably show any inefficient or incompetent administration under municipal ownership better than other more recent ventures in civic control. The investigation was intended to cover certain social and economic phases of municipal ownership as well as its technical aspects. Hence the character of the people and their cities will be discussed together with the administration, organization, financing, physical equipment and rates of the municipal electric light and power departments.

Social Considerations

It would be a very difficult matter indeed to differentiate between the people of the various cities under discussion, but as a class they have some distinct characteristics. In the first place the Canadian West is a "young man's country." The residents of the cities generally came west as young men

and have seen the country develop. All are optimistic and boosters of the West in general and of their own locality in particular. They have learned to cooperate in many lines, such as boosting real estate ventures, etc., and this has had a very marked effect on the conduct of municipal affairs. In fact this spirit of cooperation is the real basis of the success of their municipal ownership ventures. The cities that have not developed this spirit to the fullest extent are those that have had troubles with politics and local interference in the administration of their utilities.

The people of these Western cities were the restless and ambitious elements of the United States, Eastern Canada, the British Isles and foreign countries. The British sentiment is very strong and carries with it the imported ideas of municipal ownership. The readiness of the Canadian and American elements to try any new system that appeared reasonable and promising, accounts for the early acceptance of these principles of civic control and operation. Another characteristic that is peculiar to the West is the general lack of class distinctions.

This democratic condition has resulted in a better mutual understanding and a wider range of interests between all members of the community. Political machines are harder to build up under such conditions and there has apparently been less keen competition for positions in civil employ. The fixed compensation in such work appeals less to the average individual than the gambling chances of other classes of business.

Characteristics of the Cities and their Utilities

Manitoba, Alberta and Saskatchewan are primarily agricultural provinces at the present time, although the great natural resources in water power, coal, oil, gas, asphalt and iron will undoubtedly lead to great industrial development in Alberta in the near future. Of late years the urban population of these states has grown faster than that of the country districts. A partial crop failure in 1914 and the war depression brought this unnatural condition very forcibly to the attention of the people and as a result there has since been a steady trend back to the land.

British Columbia on the other hand is a land of high mountains, rolling plateaus and very fertile valleys. Its interests vary from fruit raising, ranching and other agricultural pursuits to lumbering, mining and fishing. Undoubtedly great mineral

wealth will be developed in the future although at present much of the country has not been prospected or opened up. The electrical utilities of the two largest cities, Vancouver and Victoria, are privately owned. Only one of the cities having municipal plants was investigated.

The outbreak of the European war proved a hard blow to Western Canada. Not only have tens of thousands of the best fitted young men gone to the front, but the money in the country has been diverted from local development to war purposes. The closing of the European money markets has cut off for the time being any borrowing for future development. This situation has resulted in a complete tying-up of all industry and commerce. The present financial stringency will, however, be relieved in a measure when the large crops of 1915 are marketed.

Comparatively few manufacturing industries have been established in the West. Those in operation either handle agricultural or sea products, such as in packing plants, flour mills, food product plants, fish canneries, etc., or supply the rural needs by lumber mills, cement plants, brick works and agricultural machinery shops. In the natural gas district around Medicine Hat, metal-working industries such as machine shops, brass foundries, rolling mills and also glass works, have been started and will no doubt expand with the growth of the country.

The cities selected are the larger ones of the Western provinces These have been characterized by extremely rapid growth within the last fourteen years, as shown by Table I. At the same time they have been exploited by real estate speculators until land values became greatly inflated in 1914. This resulted in a financial collapse just before the war broke out.

An example of this exploitation is to be found in extensions of the municipal street railways which were frequently made under political pressure from the land speculators. Generally such extensions have not paid for themselves and are now a source of considerable loss to the city. Each city council has had full power to undertake such expense and in boom times the people allowed them to do so. It would seem advisable to have some provincial executive board independent of the city's governing body which would have authority to restrain such needless exploitation and to act as a brake on too-confident municipal administrations.

Brief outlines of the characteristics of each of the cities con

sidered and of the history of their municipal electric plants will be given in the following paragraphs.

Regina is the capital of Saskatchewan and as such will always be a city of importance. Its growth has been more steady than that of other Western cities and it is built up with fewer outlying subdivisions. This consolidated condition makes it an easy city to serve with electric light and power, but a poor city for financially successful street car operation. It has no manufacturing industries of any consequence.

The city first built a power plant in 1904. Additions were made to this old plant from time to time until 1914 when its undesirable location making further extension inadvisable, a new plant was built. This new station will take care of all future growth for many years. The fixed charges on the old and new plants form a considerable item in the cost of electricity. The increased operating economy of the new plant will, however, practically offset the increased fixed charges. This economy will become more appreciable as the plant increases its output.

TABLE I.—DATA ON SIZE OF CITIES.

City.	Estimated present population	Population as per 1911 census.	Population as per 1901 census.
Kamloops, B. C.	5,500		
Medicine Hat, Al'ta	9,000	5,603	1,570
Lethbridge, Al'ta	10,000	8,050	2,072
Moose Jaw, Sask	20,000	13,823	1,558
Saskatoon, Sask	25,000	12,004	113
Regina, Sask.	40,000	30,213	2,249
Edmonton, Al'ta	50,000	24,900	2,626
Calgary, Al'ta	80,000	43,704	4,392
Winnipeg, Man.	200,000	128,157	42,340

Saskatoon is the leading city of central Saskatchewan and is the seat of the Provincial University. It is a large distributing center and also has large mills producing food products.

Its first municipal station was started in 1908. On account of the city's growth, this was superseded in 1911 by a new plant. But in this plant too, proper provision was not made for the rapid growth of the city and as a result it has been necessary to replace reciprocating engines by steam turbines of

greater capacity. The present plant is well situated and is now equipped for economical operation, but is somewhat handicapped by extremely high coal costs due to freight rates on the long haul from the Alberta mines.

Moose Jaw has always been a railway town, the Canadian Pacific Railway having maintained large car shops at this point for many years. Its other industries include flour mills, a packing plant, etc.

The city undertook the production of electric power in 1904. The power plant was burnt down about 1912 and was a total loss. Afterwards a new plant was built on the same site. This additional expenditure has serious effects on the city's finances and as a result the new plant was not fully equipped when war broke out. The plant is well laid out and when finished should give good service.

These Saskatchewan cities are all in prairie country and have no nearby available supplies of water power, cheap high-grade coal, or natural gas. A private corporation has recently proposed to pipe natural gas to them from the Alberta gas fields. The city of Regina has made an agreement with this company to buy the gas at wholesale at the city limits and will sell it to customers from a municipally-owned and operated distribution system, which the city will install. Meanwhile all power must be derived from coal brought either from Alberta or from the Great Lakes. It therefore seems improbable that they will become great industrial centers in the near future. Their further growth will depend then on their natural development as distributing centers.

With neither water power or cheap coal at hand, it is probable that few attempts will be made to transfer their public utility power loads to private corporations. Quite recently, however, a suggestion was made to supply them with electric power derived from low-grade lignite coals which occur in large quantities in the southern section of the province and are an extension of the North Dakota fields. Even in case such a project is successfully completed, it is probable that the cities would buy the power at wholesale rates at a local terminal station and continue as before to sell it to customers from their own distribution system, retaining their present municipal plants as reserves.

In contrast to those of Saskatchewan, the cities of Alberta have large coal fields near at hand, while Calgary has also cheap

water-power. It is therefore natural to expect considerable industrial development in these cities in the near future.

Medicine Hat, besides having coal deposits practically under the city, is located in the center of the most extensive of the Alberta natural gas fields. It is thus assured an ample supply of cheap fuel. Although built in the rolling, dry belt of Alberta, the presence of the natural gas has resulted in a more rapid industrial growth in this city and surrounding towns than in any other city in the West. Reference has already been made to several of these plants.

Natural gas is used throughout the city for all domestic purposes such as heating, cooking and largely for lighting as well. It is also used for street lighting. The success of a municipal electrical plant under such conditions was therefore doubtful and it was not decided to build such a plant until 1911. At first a gas engine plant was installed, but in November 1913 a new steam turbine plant was put in operation and took the load formerly carried by the gas engines. This change was made largely on account of the high first costs and repair charges on the gas engines, which resulted in high power costs. A very simple plant was installed without superheaters or economizers, for the gas used under the boilers was supplied by the city's own wells at a very low cost.

The demand for power for industrial purposes developed very rapidly until war broke out. It is probable that this demand will increase again with the re-adjustment of conditions after the war.

Lethbridge in Southwestern Alberta is the center of an extensive colliery district and serves as a distributing point for the surrounding towns. Although well supplied with coal and natural gas it has not developed any industries except those connected with mining. All the collieries have their own plants.

The city bought out the electrical plant of a private company in 1908. This plant was uneconomical in operation and poorly located. Work was started at once on a new plant. The old station burnt down in December 1909 just before the new plant was complete. The location of the new station, while favorable for operation, was such that construction costs were excessive and in consequence the plant has high fixed charges.

The municipality owns and operates its own coal mine on leased land adjacent to the plant. On this account it has the cheapest coal supply of any city in the West.

Edmonton is the capital of the Province of Alberta and is the

location of the new Provincial University. It embraces about 56 square miles within its boundaries as a result of real estate exploitation. Its industrial works consist principally of two packing houses, lumber mills, flour mills, brick yards, etc. It is expected that the great undeveloped sections of Northern Alberta will contribute largely to the future prosperity of this city as it is the natural outlet for the whole north country.

There are seams of lignite coal under the city itself, while higher grade coal occurs in great quantities to the west of the city. Several undeveloped water power sites in the neighboring country are available for power development.

Edmonton's municipal power plants have had interesting histories. The first electric station and pumping plant was built on the banks of the North Saskatchewan River apparently with no consideration of future developments. This plant soon reached its maximum capacity and a producer gas power plant was installed in an adjoining building to furnish additional electric power. A separate pumping station was next built a short distance from the old plant. It was provided with its own boilers and with a vertical reciprocating pumping engine placed in a pit. In a few years another steam power plant was erected beside the producer gas building with reciprocating engines and hand-fired boilers. Later this was extended and steam turbines and boilers with mechanical stokers were installed, several steam engines were scrapped, and the original station definitely abandoned. In the meantime the pumping plant was enlarged and the vertical reciprocating pumping unit was scrapped in favor of centrifugal pumps. At present the steam required by the pumping engines is supplied from the main boiler plant through a tunnel and the pumping plant boilers are permanently closed down. When Edmonton absorbed the town of Strathcona on the opposite side of the river, its electric plant and pumping station were also taken over. These operated non-condensing and were therefore uneconomical in operation. The Strathcona plant was closed up as soon as the water and electrical services could be assumed by the Edmonton station. It can thus be seen that the present municipal plant is somewhat of a makeshift. Contracts were let over a year ago for the construction of a complete new power house. But the war made necessary the postponement of these contracts. At the time of this investigation the city was considering the purchase of power from private corporations. Some of these were hydroelectric

proposals, others were from coal companies who proposed to generate power at their mines and transmit it to the city.

Calgary in Central Alberta is the leading city of the middle west. It appears to have sustained less crippling of business during the war depression than any of the other cities. On account of cheap water power, available nearby coal fields and its supply of natural gas, it is developing into an important industrial center. Among its principal industries are the big Ogden car shops of the Canadian Pacific Railway, a cement mill, a packing plant, soap works, lumber mills, flour and food product mills, etc.

Calgary started its first municipal plant in 1905 and kept adding to it until 1911 when a new plant, in a more favorable location, was put in service. About the same time a private corporation, the Calgary Power Co., which now has 31,500 h.p. available in its two hydroelectric stations, entered into a contract with the city to supply it with power up to 8000 h.p. But on account of low water at the time of the winter peak loads, the city has had to maintain its plant at a capacity capable of carrying the full load in an emergency. The fixed charges on this steam plant now form a considerable proportion of the cost of power.

A private corporation, the Eau Claire & Bow River Lumber Company, serves customers in the central part of the city with electricity partly derived from water power and partly from a steam plant. This company had a franchise previous to the establishment of the municipal plant. Another private company has a franchise to supply natural gas for domestic purposes at a cost of 35 cents per 1000 cubic feet. Much domestic lighting is done with gas. Hence the load on the municipal plant is not so large as would be the case if it had a monopoly of the lighting business as in other cities.

Half of the boilers in the municipal plant are fired by gas of 1000 B.t.u. per cubic foot and costing 15 cents per 1000 cubic feet. The others burn coal. The plant is well designed and well equipped and when in continuous operation produces very cheap power.

At present an agreement for one year is in force between the city and the Calgary Power Company whereby the latter supplies the full city demands for power at a low figure and has the use of the municipal steam plant for emergencies. The Calgary Power Co. pays all operating and maintenance costs

at the municipal plant, which is still handled by the regular city operating staff. The company does not, however, pay any of the plant's fixed charges.

The steam plant is arranged for ample future development. At the present time, several additional hydroelectric proposals are receiving consideration. With an abundant supply of cheap water power further additions to the steam plant may become unnecessary.

Winnipeg is the largest city in all Western Canada, and being the outlet to the east of all the western railroads, it has great future possibilities.

A private corporation, the Winnipeg Street Railway Co., had a franchise to furnish electric power and operate street railways very early in the history of the city. Up to 1907 this company charged 20 cents per kw-hr. for lighting. In that year it put into operation its hydroelectric plant at Lac du Bonnet and reduced the rate to 10 cents per kw-hr.

In the meantime the citizens recognized that only by having a supply of very cheap power could they hope to see Winnipeg become an industrial center and they voted money in 1906 for building a municipal hydroelectric plant which was completed and put in operation in 1911. The rates quoted to its customers were much below the former prices of the railway company. In 1914 the municipal plant at Point du Bois had a generating capacity of 22,500 h.p. which has since been increased to 50,000 h.p. The total power available at this plant is 100,000 h.p. The design and operation of this plant have received much attention in the technical press and will not be described here.

Kamloops was the only city in which inquiries were made in British Columbia. It is located at the junction of the North and South Thompson Rivers in the central section of the province. Kamloops is a divisional point on two transcontinental railroads. The surrounding country is a rich agricultural and fruit district. Some mining is carried on in adjacent sections and it is probable that this industry will increase in importance as the country develops.

The city's first municipal plant was built about 1907. Owing to the rapid growth of Kamloops this plant proved inadequate and a new municipal electric plant of 1200-kw. capacity was built in 1912 together with a new pumping plant on a site east of the city where an excellent water supply was available from

the South Thompson River. But owing to the high price of fuel, it was decided to develop a hydroelectric site at Barriere about 18 miles north of the city. Unexpected difficulties were encountered in the construction of this plant and it was not put in service till the beginning of 1915. It has a capacity of 1500 kw. which can be increased later as the load builds up. The transmission line to the city carries 44,000 volts with a step-down transformer station at the steam plant. The cost of this hydroelectric system far exceeded the original estimates and the steam plant is still held as a relay, consequently the electric service of the city has to bear very high fixed charges due to these two plants.

Other utilities owned by the various cities and some general information regarding them is given in Table II. Besides those undertakings given in the table, practically all maintain municipal hospitals.

Organization of Utilities

The organization of the municipal governments varies somewhat in the different cities. However, it is generally the practise to have three commissioners in charge respectively of Finance, Utilities, and Public Works and Welfare.

In some cases these are elected by the people and in other cases are appointed by the city's common council. At Lethbridge the public utility commissioner acts as superintendent of the electric light and power department and of the street railway system. Generally, however, a superintendent is provided for each utility. In the case of Calgary and Edmonton, the city's electrical engineer takes charge of the distribution of the current from the plant's switchboard.

In general the superintendents of these municipal utilities are capable men and are exerting as much energy to secure economical results as if they were employed by private corporations. Most of them have held their positions for a considerable length of time and have virtually developed and built up their utilities. These executives are not likely to be subject in municipal service to as much pressure and driving from high officials as in the case of superintendents with private concerns. Hence their success is largely a measure of their own personal initiative.

All the provinces have very stringent boiler inspection and engineer's licensing laws, and as a result, the operating engi-

TABLE II.—DATA ON PUBLIC UTILITIES.

City	Electric light and power	Electric street railway	Water works	Sewage	Gas	Other utilities	Source of water supply
Kamloops, B. C....	Municipal	None	Municipal	Municipal	None	....	South Thompson R.
Medicine Hat.....	Municipal	None	Municipal	Municipal	Municipal	....	South Saskatchewan R
Lethbridge.........	Municipal	Municipal	Municipal	Municipal	Private Corporation	Coal Mine	Belly River
Moose Jaw.........	Municipal	Private Corporation	Municipal	Municipal	None	Cemetery	Local Creek
Saskatoon..........	Municipal	Municipal	Municipal	Municipal	None	Cemetery	South Saskatchewan R.
Regina............	Municipal	Municipal	Municipal	Municipal	None	Stock Yards	Lake Wascawa
Edmonton.........	Municipal	Municipal	Municipal	Municipal	None	....	North Saskatchewan R.
Calgary...........	Municipal	Municipal	Municipal	Municipal	Private Corporation	....	Elbow River
Winnipeg.........	Municipal	Private Corporation	Municipal	Municipal	Private Corporation	....	Hydro Plant Winnipeg River.

neers in the various plants are all high grade men. The firemen, as a rule, are men working up for a license and consequently take an interest in their plant and in their work. Such operating forces should be able to give the superintendents valuable aid in obtaining economical results.

In only one case did there seem at present to be any politics in the organization of the plant. This city, however, has had a long record of political and civic-council interference with the operation of its utilities, greatly to their detriment. Another city is said to have had similar experience in the past but seems to have overcome these evils at the present time. Considerable criticism was heard in Edmonton in regard to the operation of the city's municipal street railway system. Its employees had formed a union and were said to dominate the management of the system through their political influence. An attempt was being made at the time of this investigation to drag the municipal street railway system of Calgary into politics. This utility has up to the present time been the most successful civic tramway in the West and holds a record for good service and competent management.

No civil service laws are in force other than the necessary licensing of engineers. The superintendent engages and discharges the men under him and generally promotes his own men as openings occur and the men have the necessary legal and administrative qualifications.

It has been urged against municipal ownership that more men are employed than would be the case in private plants. In those cities where politicians are said to have interfered with the utilities there seemed to be some evidence of an excess of men, and a laxity of discipline. But in the other cities the plants appeared to have the minimum number of men necessary to properly carry on operation. The new municipal plant at Regina is a striking example of careful layout and operation to reduce labor to a minimum, as very few men are needed to run this station.

Another interesting fact is that almost all plant employees are under middle age. One may partly account for this condition by the use of recently developed machinery to which the older men have not adapted themselves.

A very necessary factor for obtaining efficiency in planning and operating a utility, is continuity of management. If a spoils system exists in municipal politics one cannot expect the

city's public utilities to be either well managed or suitably equipped. The spoils system as generally understood does not seem to exist in any of these cities. On the other hand Edmonton has suffered severely from too frequent changes in the management of its utilities. The new man coming in was usually forced to complete work unfinished by his predecessor and with which often he was not fully in sympathy. Then he also was liable to removal before he had his plans for improvement fully carried out. This has resulted in the heterogeneous assortment of equipment and the odd station lay-out already described.

Power Plants and Equipment

All of these cities as shown in Table I have grown very rapidly in a very short period. This rate of growth could hardly be foreseen in any particular city for other towns equally favored did not develop so rapidly. Hence much of the earlier plant equipment due to small size and poor operating economy has become obsolete. There has, therefore, been in each city a rebuilding of old plants and the construction of new plants as noted in preceding paragraphs.

The power plant buildings in most cities are of the usual construction with steel framing and brick walls with the usual arrangements for lighting, ventilation and traveling cranes. Regina's plant, however, is an exception. Here the city went to considerable expense to make its new plant conform with the general plan of buildings to be erected on the adjoining Governmental reserve. Saskatoon's plant also shows a considerable amount of architectural taste.

Table III gives some general data on the equipment of the various plants. All have standard B. & W. water-tube boilers equipped with superheaters except in the cases of Medicine Hat and Kamloops. Induced draft fan equipments are used everywhere except in Kamloops. At Regina forced draft fans are also used in connection with the mechanical stokers. At Edmonton an "évasé" or Venturi form of induced draft stack is used, where a 20-h.p. motor drives the fan necessary to serve 2000 b.h.p. The Kamloops plant has a six-ft. concrete chimney 185 ft. high.

A question arises as to whether a chimney and natural draft would not be more economical in some cases. At Regina on account of the proximity of the Parliament Buildings and Park, a chimney was not permitted. In several cases the

TABLE III.—STEAM PLANT EQUIPMENT.

City	Generator capacity	Boiler capacity	Economizers	Main engine equipment.
Kamloops.	1,200 kw.	4 Boilers 1000 h. p.	None	2— 600 kw. Curtis Turbines.
Medicine Hat.	3,000 kw.	4 Boilers 1600 h. p.	None	2— 750 kw. Curtis-Rateau Turbines. 1—1500 kw. Curtis-Parsons Turbine.
Lethbridge.	2,300 kw. 2 phase	8 Boilers 2260 h. p.	1–Green 1–Sturtevant	1— 300 kw. Compound H. S. Engine. 1— 500 kw. Triple Expansion H. S. Engine. 1—1500 kw. Curtis-Parsons Turbine.
Moose Jaw.	3,000 kw.	8 Boilers 2600 h. p.	Sturtevant	1— 500 kw. Curtis Turbine. 1—1000 kw. Curtis Turbine. 1—1500 kw. Curtis-Parsons Turbine.
Saskatoon.	5,950 kw. 2 phase	8 Boilers 4000 h. p.	Green	1— 750 kw. Compound Corliss Engine. 1—2000 kw. Parsons Turbine. 1—3250 kw. Parsons Turbine.
Regina.	7,600 kw.	Old Plant 4 Boilers 1600 h. p. New Plant 8 Boilers 2600 h. p.	Sturtevant	1— 300 kw. Corliss Engine. 2— 400 kw. D. C. Engine Units. 1— 500 kw. L. P. Parsons Turbine. 2—1500 kw. Curtis-Parsons Turbines. 1—3000 kw. Curtis-Parsons Turbine.
Edmonton.	10,250 kw.	16 Boilers 7000 h. p.	None	2— 400 kw. D. C. Compound Engines. 1— 750 kw. D. C. Triple Expansion Engine. 1— 700 kw. Producer Gas Engine. 1—1000 kw. Compound Corliss Engine. 1—1000 kw. Parsons Turbine. 1—2000 kw. Curtis-Parsons Turbine. 1—4000 kw. Curtis-Parsons Turbine.
Calgary.	11,350 kw.	16 Boilers 5430 h. p.	None	1— 600 kw. Triple Expansion Engine. 1— 500 kw. Triple Expansion Engine. 1— 750 kw. Compound Corliss Engine. 1—2000 kw. Parsons Turbine. 1—2500 kw. Curtis-Rateau Turbine. 1—5000 kw. Parsons Turbine.

power plants are located beside rivers in the bottom lands under the bluffs and it was feared this might prevent a chimney from providing draft unless of excessive height. In general, however, it is claimed that radial brick and concrete chimneys were too expensive to commercially compete with the induced draft plants.

Underfeed stokers are giving good satisfaction at Regina. Natural gas is burned in Gwynne burners in Medicine Hat's plant and in part of the Calgary station. Chain grate stokers are in use in all other plants except Kamloops. Hand fired grates were installed at Kamloops where wooden slabs from the lumber mills are burned part of the time as fuel.

Coal and ashes are almost universally handled by bucket conveyers. The coal is stored in elevated bins above the firing aisle. The ashes are elevated into storage bins convenient for loading railroad cars. Most plants are now provided with equipment for analyzing and testing their coal. Several practically buy coal on the heat unit basis. Economizers are used where coal is expensive and therefore when full utilization of heat is of first importance.

In the newest installations there is a decided tendency towards motor drives for all auxiliaries.

Admiralty-type feed pumps are installed in many plants though the simple turbine-driven centrifugal boiler feed pumps have been used in two cases.

The waters of Western Canada generally contain scale forming salts which make them unsuitable for boiler feed. However, there is no uniformity of treatment of the feed water. Some plants soften it while others use boiler compounds. All use feed water heaters. The condensate from the surface condensers is returned to the boilers in every station.

The adoption and use of instruments to increase boiler room economy is universal. Coal as a rule is automatically weighed and recorded. Gas burned under boilers is metered. The boiler feed water is generally measured by V-notch recorders which have universally given good satisfaction. Venturi meters are employed in some plants. CO_2 recorders are in use in almost all plants. Steam flow meters have been installed in a few cases. Many plants are equipped for making complete tests and these are carried out at regular intervals either to determine the best coal to use, or to learn the most economical methods of operation.

The older generating equipment consisted of steam engines, usually of the vertical high speed or Corliss types. Steam turbines have been provided in all recent installations. It is interesting to note in Table III the predominance of Parsons and Curtis-Parsons units. The number of British machines is also a striking feature. Recent purchases indicate an increasing preference for European machinery. The preferential tariff to the British Isles has something to do with this condition, though the most recent order—a 6000-kw. turbo-generator for Edmonton, was taken by a Swiss company.

Usually the condensers are supplied by the party that furnishes the main turbine. These are all of the surface type and give little trouble from tube failures with the cooling water used. All foreign condensers are provided with vacuum augmentors of various types and are usually supplied with three-throw motor-driven air pumps, which maintain high vacuum.

In electrical machinery, the use of European equipment is even more noticeable than in the case of the engines and turbines. The switchboards with one exception are of American manufacture and have been built according to modern practise.

All the larger plants are provided with some machine tools to enable them to make their own repairs. Fine toilet rooms, wash rooms and lockers have been provided in many stations for the men.

In Saskatoon, on the initiative of the superintendent, a society for mutual improvement along technical lines was formed among the utility's employees. Apparently this has not been attempted in other places and outside of local engineering societies there seems to be no organized effort to educate the men in technical subjects.

The Winnipeg plant, being hydroelectric, is not included in the preceding general statements. The plant is built on the Winnipeg River, 77 miles from the city. The power is carried into town over a high-tension transmission system. During construction it was necessary to build an electric tramway to the plant to convey the needed materials and machinery. This is still retained and operated by the city.

On the basis of these facts it may be stated that as a whole the municipal power plants of these cities are up-to-date in the matter of physical equipment, though often retaining some of the older units as reserve. They are also provided with competent staff and modern instruments to ensure efficient operation and low unit production costs.

Distribution Systems

In considering distribution systems, it must be remembered that the cities are new and are scattered over large areas. This in a measure simplified wiring problems although provisions for future growth have made necessary many underloaded circuits and transformers. In those cities where the total output is metered the distribution losses run from ten to eighteen per cent of the current generated.

The consulting engineers who were employed in laying out the first plants of several of these cities insisted on two-phase alternating-current systems. Most plants have been entirely changed over to three-phase, but at least two cities are still operating with two-phase machinery and distribution systems involving unnecessarily high first costs and maintenance charges.

Distribution systems are generally at 2300 volts except in some cases where 6600 volts is carried to substations. The use of 2300-volt motors for power service is increasing. The starting devices used with these motors are more complicated than with lower voltages, but being without transformers, the net efficiency of the service is higher.

In two cities the distribution system is in charge of an electrical engineer and is independent of the power plant superintendent. In general, however, the whole electric light and power utility is under the supervision of one man and this seems to be the more desirable and more efficient condition.

Cost and Financing of Utilities

All of these utilities are financed by loans on municipal debentures whose terms vary from 20 to 35 years and longer, and bearing interest at rates of 4 to 6 per cent. Most of these were marketed in Great Britain, though a few were placed in Eastern Canada and in the United States. The expansion of Western Canada was so rapid before the war, that fears were expressed in financial circles that these cities were exceeding their ability to meet these obligations. Hence recent debenture issues have had to bear higher interest than earlier ones on this account. The war, however, has closed all money markets and the West, being without funds to carry on development, has felt the resulting depression much more keenly than the East.

The municipalities provide for the retirement of these de-

bentures by the maintenance of sinking funds. Interest and sinking fund charges must be met out of the current revenue of the utility and in general, rates are adjusted to produce these funds together with a small surplus for emergencies.

An attempt has been made in Tables IV and V to summarize the financial statements for the year 1914 of the various utilities discussed. In every case possible the auditor's statements were used as a basis for the analysis. The kilowatt rating of the plants is that of the machinery available for service. The plant value per kilowatt capacity in Table V seems high in several cases. This usually covers obsolete machinery still carried on the books, together with the costs of errors and mistakes made in building up the plant from a small station. The power output of the plant in kilowatt-hours was used as the basis for the figures in Table V which shows all costs on a kilowatt-hour basis. Table V also includes average figures in nineteen Massachusetts steam power plants for 1914, based on the returns of the companies to the Board of Gas and Electric Light Commissioners of that state.

In connection with the high first costs of the distribution systems and the yearly distribution costs, attention is drawn to the fact that these cities have grown up with homes scattered over large areas. The municipal utility has had to supply all reasonable demands for light and power even in the most outlying districts. This has resulted in high pole and line expense and correspondingly high upkeep charges.

The capital cost for the hydroelectric plant at Kamloops has been so great that its fixed charges will nearly equal the former cost of fuel in the steam plant. But the labor cost will be less than before. Hence the net cost of power will not be appreciably decreased by the use of hydroelectric power unless the load factor of the plant can be greatly increased. Efforts are being made to secure additional mining and irrigation loads.

It has been said that the electrical utility at Medicine Hat does not pay enough for the gas that it consumes and that if it were charged the same rates as other consumers, the surplus would be wiped out and higher rates might even be necessary.

In the Moose Jaw statement in Table IV, a deduction of $9,012.00 is made from the total cost. This covers the charges for operating the city pumping station which is connected with the electric plant and operated by the same force. Hence for purposes of comparison in Table V, this cost was deducted

TABLE IV.—SUMMARY FROM 1914 FINANCIAL STATEMENTS.

	Kamloops	Medicine Hat	Lethbridge	Moose Jaw	Saskatoon	Regina	Edmonton	Calgary	Winnipeg
Present population	5500	9000	10,000	20,000	25,000	40,000	50,000	80,000	200,000
Rated kw. of plant	2700	3000	2300	3,000	5,950	7,600	10,250	11,350	30,000
Total debenture issue	$506,500.00	$430,000.00	$689,665.73	$707,853.39	$1,047,665.10	$1,486,333.34	$2,830,190.99	$2,029,202.28	$7,412,000.00
Value of plant	$502,693.49	$368,142.89	$456,370.78	$354,071.80	$570,000.00	$704,464.20	$1,955,091.06	$976,287.09	$3,962,144.49
Value of distributing system			$139,757.37	$190,446.68	$430,000.00	$625,031.61	$745,985.94	$1,188,921.37	$2,904,779.09
Kw-hours generated	2,628,100	3,050,070	3,415,000	3,739,990	8,873,642	9,315,355	21,927,089	31,391,596	62,493,162
Kw-hours metered	2,338,912	......	......	3,031,246	7,966,920	8,223,895	......	......	......
Net revenue	$84,692.89	$49,251.08	$110,898.53	$179,428.26	$340,628.08	$326,435.73	$767,870.71	$670,512.24	$976,347.50
Cost of coal	$4.90	(Natural Gas)	$1.20	$3.40	$6.66	$5.40	$3.22	(Gas and Water Power)	(Water Power)
Operating Costs									
Fuel	$35,271.92	$1,000.00	$12,562.55	$53,624.12	$121,296.68	$131,565.43	$165,238.86	$48,735.17	......
Wages	13,951.78	12,721.98	14,953.84	21,531.98	28,972.22	41,023.17	78,619.25	32,056.20	$41,330.32
Water	......		720.00	1,698.25	2,605.71	824.48	1,538.40	5,048.00	......
Oil, waste, supplies etc.	1,094.01		2,452.76	5,257.74	3,950.73	5,509.54	7,272.25		8,538.79
Repairs and maintenance	98.26		7,627.23		11,541.90	10,549.25	56,919.81	11,732.74	29,621.02
Distribution Costs									
Wages	1,804.17	3,350.87	1,357.05	9,941.24	17,595.59	4,703.30	34,739.23	80,648.89	8,552.96
Repairs and maintenance			7,314.77	11,450.95		14,594.73			36,786.47
Miscellaneous	......	135.41	......	3,183.94	......	4,425.93	7,403.57	166,075.84	109,532.18
Overhead Costs									
Salaries	4,012.95	3,593.25	5,529.44	2,475.00	19,424.56	14,482.53	41,722.66	71,379.48	55,290.00
Office expenses	375.97		2,767.85	8,218.34			6,208.99		34,041.16
Insurance	603.47	......	575.92	1,001.14		2,324.70	1,949.45	3,224.52	182.20
Taxes	......	......	8,114.67	1,028.95	......	......	4,824.68	8,675.24	4,007.05
Employers liability insurance	......	......	514.65	1,578.34	......	......	......	......	......
Fixed Charges									
Interest	10,225.20	14,821.95	30,071.15	29,704.47	45,690.22	63,107.93	175,063.84	93,339.97	305,526.11
Sinking funds	4,147.80	13,004.26	16,069.72	......	20,983.77			35,612.94	......
Depreciation	......	......	......	24,865.13	29,967.76	19,370.65	106,606.82	36,125.29	264,254.52
Total Cost				175,559.59		311,481.64			
Less deductions				9,012.00		7,001.62			
Net cost	71,585.53	48,627.72	110,631 60	166,547.59	302,029.14	304,480.02	688,107.81	592,654.28	897,662.78
Surplus	13,107.36	623.36	266.93	12,880.77	38,598.94	21,955.71	79,762.90	77,857.96	78,684.72

TABLE V.—COSTS PER KW-HOUR GENERATED, 1914.

	Kamloops	Medicine Hat	Lethbridge	Moose Jaw	Saskatoon	Regina	Edmonton	Calgary	Winnipeg	Average of 19 Mass. Cities.
Present population	5,500	9,000	10,000	20,000	25,000	40,000	50,000	80,000	200,000	66,700
Rated kw. of plant	2,700	3,000	2,300	3,000	5,950	7,600	10,250	11,350	30,000	7,530
Kw-hours, generated	2,628,100	3,050,700	3,415,000	3,739,990	9,716,142	9,315,355	21,927,089	31,391,596	62,493,162	11,010,000
Cost of coal	$4.90	(Natural Gas)	$1.20	$3.40	$6.66	$5.40	$3.22	(Gas & Water Power)	(Water Power)	$3.65
Plant cost per kw. capacity	187.59	122.71	198.42	118.02	95.80	92.70	190.75	86.01	132.07	....
Distribution system cost per kw.			60.76	63.48	72.27	82.25	72.80	104.75	96.82	....
Net Revenue per kw-hour	3.222c.	1.612c.	3.247c.	4.797c.	3.838c.	3.504c.	3.504c.	2.136c.	1.562c.	....
Operating Costs										
Fuel	1.342c.	0.033c.	0.369c.	1.298c.	1.367c.	1.412c.	0.754c.	....	....	0.570
Wages	0.531		0.438	0.527	0.326	0.440	0.358	....	0.066	0.216
Water	....	0.417	0.021	0.045	0.029	0.009	0.007	....	....	0.022
Oil, waste and supplies	0.041		0.071	0.140	0.045	0.046	0.033	....	0.014	0.008
Repairs and maintenance	0.004		0.223		0.130	0.087	0.260	....	0.047	0.092
Total Operating Cost	1.918	0.450	1.122	2.010	1.897	1.994	1.412	....	0.127	0.908
Distribution Costs										
Wages	0.069	0.109	0.040	0.266	0.199	0.051	0.158	....	0.014	0.198
Repairs and maintenance			0.214	0.306		0.121		....	0.059	0.225
Miscellaneous	....	0.004	....	0.085	....	0.047	0.034	....	0.175	0.147
Overhead Costs										
Salaries	0.153	0.117	0.162	0.066	0.219	0.156	0.191	....	0.088	0.344
Office expenses	0.014		0.081	0.226			0.028	....	0.055	
Insurance	0.023	....	0.017	0.027	....	0.025	0.009	....	0.000	....
Taxes	....	....	0.237	0.027	....	....	0.022	....	0.006	0.314
Employers' liability insurance	....	....	0.015	0.042	....	....	....		....	....
Production Cost	2.177	0.680	1.888	3.055	2.315	2.394	1.854	1.362	0.524	2.136
Fixed Charges.										
Interest	0.389	0.486	0.881	0.763	0.515	0.666	0.798	0.297	0.489	....
Sinking funds	0.158	0.426	0.470	....	0.236			0.113	....	....
Depreciation	....	....	....	0.635	0.337	0.208	0.486	0.115	0.423	....
Net Cost	2.724	1.592	3.239	4.453	3.403	3.268	3.138	1.887	1.436	....
Surplus	0.498	0.020	0.008	0.344	0.435	0.236	0.364	0.247	0.126	....

proportionately from the operating costs and the overhead costs. The Moose Jaw plant was partly under construction in 1914, which accounts for a portion of its high production costs.

The deductions in the cost of Regina in Table IV represent the value of extra stock on hand in the store rooms at the end of the year. Hence in order to obtain the values in Table V, this was deducted proportionately from the costs of oil waste, etc., from repairs and maintenance of plant and from repairs and maintenance of the distribution system.

Regina was not using its new power plant during all of 1914. Its economical operation ought to make material changes in the power costs of the year 1915.

At Edmonton the Power Plant department has control of the generation of electricity and the pumping of water. It delivers the electricity at its main switchboards or at the direct-current switchboards of its substations either to the street railway or to the electric light and power department which is a separate organization. The report of the superintendent of the power plant showed the operating costs of the steam, gas, water and filtration departments but did not distribute the overhead charges between these subdivisions.

In Table IV the interdepartmental charges were first distributed proportionately among the different items in the summary. Then the overhead charges were distributed on the basis of the total operating costs of the electrical and water plants. This allotted 75 per cent of the overhead charges to the electrical plant and 25 per cent to the water pumping and filtration plants. The latter charge amounted to $10,082.99.

A further analysis of the statements showed a deficit in the water pumping and filtration departments between total revenue and operating costs of $1,119.98. Both this charge and the preceding one of $10,082.99 had evidently been made up out of the revenue of the electrical departments and in Table IV are therefore included in its surplus since the water department operated at a loss.

In addition, the city council in By-law No. 526 set aside the sum of $12,481.26 out of the surplus of the power plant. For the purpose of this analysis this sum is still treated as surplus for the electrical department.

Finally, the statement of the power plant department showed a net surplus over all charges, including the reserve just discussed, as shown by its profit and loss account for 1914, to the

amount of \$828.33. This also was evidently earned entirely by the electrical department. The true net surplus for the year was therefore \$24,512.92.

The electric light and power department of Edmonton has charge of the distribution and sale of its electricity to private consumers. It is an entirely distinct and separate organization from the power plant department and keeps its own sets of accounts. However in these accounts the selling price of the power plant department for electricity is the cost price to the electric light and power department. For the purposes of this discussion, it seemed advisable to combine the statements of the two departments and this was done in Tables IV and V. The electric light and power department showed a net surplus for the year of \$55,190.95. Hence the total surplus from the electrical utility was \$79,762.90.

The miscellaneous charge for the city of Calgary includes an item for \$150,821.63 which was the cost of 26,463.032 kw-hr. purchased from the hydroelectric plants of the Calgary Power Company. This represents an average cost of 0.57 cents per kw-hr. at the city's terminals. Although the city's municipal plant generated the balance of the power used, *i. e.*, 4,928.564 kw-hr., it did not seem fair to make a distribution of costs in Table V on this basis for most of the costs in this plant included "stand-by" charges for keeping the boilers warm and under steam and for having a sufficient labor force on hand in case of emergency demands for power.

The fiscal year for Winnipeg ends April 30th. The figures shown in Table IV and V are for the year ending April 30, 1915, and therefore cover a longer war period than those for the other cities. There may be some difference of opinion regarding the classification of these accounts in Table IV. The figures for wages include the following:

Labor, Hydraulic Plant....................	\$15,392.21
Inspection and Patrolling, Transmission System	6,414.68
Terminal and Substations, Operating Labor....	19,523.43
	\$41,330.32

The repairs and maintenance costs cover charges similarly distributed. Office expense cost consists of commercial expense of promotion and collection, general office expense, printing and stationery, and war tax. The miscellaneous costs consist of the following:

Tramway to plant, operation and maintenance	$33,795.34
Extraordinary contingencies	18,076.45
Uncollectable accounts	12,000.00
Expenses on consumers' premises and municipal lamps	8,671.80
Undistributed expense	36,988.59
	$109,052.18

Although no fund is set aside for employee's liability insurance, $9,484.60 was paid out in undistributed expense during the year for injuries and damages.

The item " kw-hr. generated " in Tables IV. and V for Winnipeg represents the kw-hr. delivered at the terminal substations. It was thought best to use this figure so that the values would be comparable with those of the other cities. The utility's records show the following:

Total kw.-hours generated	70,743,274
" " " delivered at substations	62,493,162
Line and transformation losses	8,250,112
" " " " per cent	11.6

The financial year 1914 was chosen for this analysis of the costs of these plants not only because these reports were the most recent available but also on account of the lack of abnormal conditions of growth during that period. Previous to this year the increases in electrical demands were exceedingly difficult to forecast. A curve showing the growth of electrical demand that is typical of all these Western cities is that for MooseJaw shown in Fig. 1.

The year 1914 was a poor one financially for these municipal plants. Industrial plants were closed down at the outbreak of war and the utility's power load was thus decreased. This in many cases made retrenchment necessary and all power plant improvements and extensions were suspended. A decrease in load instead of the expected increase, left all plants with excess power capacity. Consequently higher fixed costs and operating costs were the result.

Table V shows very plainly the effects of cheap gas, coal and water power on the cost of electricity in the cases respectively of Medicine Hat, Lethbridge, Calgary and Winnipeg. The two former cities have comparatively small plants which at present are much underloaded and with low load factors. The effect of the high cost of coal is seen very plainly in the costs of the Moose Jaw, Regina and Saskatoon plants. Such utilities

should therefore have the most economical plants and methods available. In fact this consideration has not been neglected, for these plants are all provided with steam turbines, economizers, superheaters, CO_2 recorders and other apparatus to improve operating conditions and to reduce plant costs.

It is scarcely fair to compare the fuel costs of these Western Canadian cities with that of Massachusetts as given in Table V, for in the West lower grades of coal with less heating value and higher ash and moisture contents are generally used. Labor also costs more in the West than in Massachusetts.

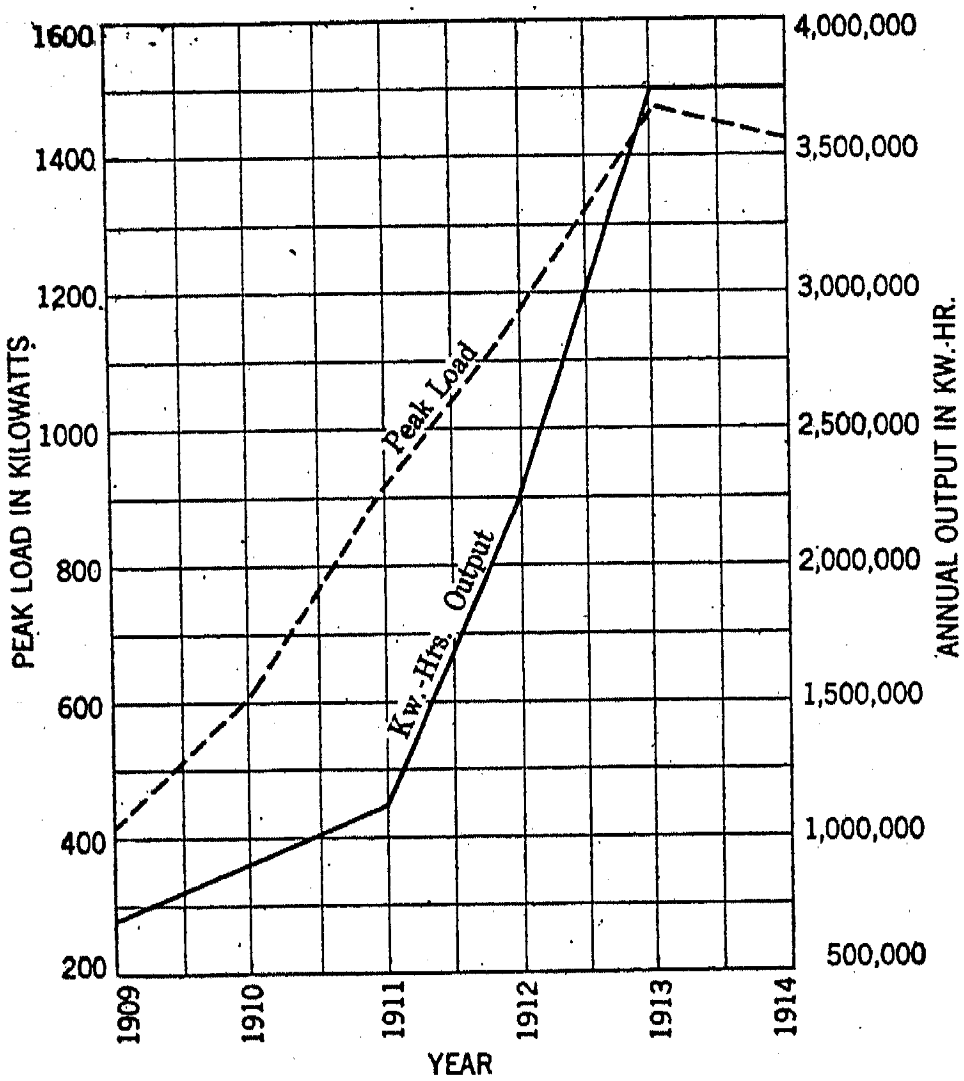


FIG. 1—TOTAL ANNUAL OUTPUT AND PEAK LOAD 1909 TO 1914—MUNICIPAL ELECTRICAL DEPARTMENT, MOOSE JAW, SASK.

TAXATION OF MUNICIPAL UTILITIES

The electrical utilities are taxed as shown in Table IV, in the cities of Lethbridge, Moose Jaw, Edmonton, Calgary and Winnipeg. Only in the case of Lethbridge has the utility been taxed near its full value. In this city, it is held that the utility enjoys the use of the city's streets and alleys for its distribution system and that its business increases with the general improvement of the town. It also receives fire protection and police protection provided by the general taxation of the city. The users of electric light and power thus enjoy privileges at the general expense of the public and should therefore pay in their rates a proportional tax to cover such extra privileges. In the other cities the taxes are only for a portion of the plant or system. The

taxes at Winnipeg probably cover property not within the city limits.

The Lethbridge system is based on the right ideas and is more nearly the correct one. In order to determine the most equitable basis for taxation of such municipal utilities it is necessary to study the classes of service they furnish and the privileges these enjoy.

An analysis of the account of the utilities will show that these may be divided into three general classes.

(A) Municipal services other than revenue-producing utilities. This class includes power and light services in municipal buildings, etc.; street lighting, and in pumping plants for fire purposes and street cleaning use.

(B) Municipal services for revenue-producing utilities such as, street railway power, power to waterworks for domestic supply etc.

(C) Private light and power consumers.

The services rendered by Class A are obviously for the benefit of the whole civic community and there is no justification for taxing the portion of the distribution system providing such service or the proportion of the generating plant necessary to supply such demands.

Class B services provide privileges which while they may be of value to the city as a whole, are enjoyed only by certain portions of its people and are paid for in proportion to the use made of this particular utility. The users of such special service should therefore be expected to pay in their rates a just proportion of the taxation on that part of the plant of the electrical utility provided to serve their needs.

It is obvious that customers in Class C enjoy special privileges in the use of the utility's light and power, and should pay for this privilege as a tax on the proportionate part of the system supplying their demands.

It is thus possible to fairly apportion the taxable and tax-free values of the electrical plant and the land occupied and used by the utility. Such apportionment for taxation purposes should be one of the duties of the Provincial Public Utility Commission.

A question naturally arises regarding the special privileges that made the utility subject to taxation. A survey of the following brief summary of certain features of these plants should indicate clearly that there is ample justification for subjecting them to taxation.

In the first place the utility occupies land with a plant, of which a portion is used for other than pure civic purposes and produces

revenue. It is therefore subject to taxation under all usual plans of assessment and particularly so in those Canadian cities under single-tax. The utility uses the city's streets and alleys for poles and conduits and enjoys fire and police protection as already mentioned. The city's credit was employed in marketing the debentures to build the plant and its credit is still used in purchasing fuel, labor and supplies. Considerable time of the city's executives is devoted to consideration of the utility's special problems and thus a portion of the cost of municipal government is rightly chargeable to the utility. The utility furthermore pays no franchise tax to the city as would be the case in a privately owned system.

Municipal plants under the conditions just enumerated are able to serve private customers at rates below the cost at which they could supply such service themselves and in this way provide these consumers with special privileges which are enjoyed at the expense of the general public when no taxes are paid. It is therefore obvious that taxes should be levied on portions of these utilities and that consumers of classes B and C should pay in their rates, additional charges to meet this taxation which in the end really represents the utility's just share of the general administrative and maintenance expenses of the city as previously outlined.

Referring to Table V, it will be seen that taxes in the case of the Massachusetts cities amount to more than the plant labor costs and form about 15 per cent of the total production cost.

Funds are set aside for employers liability insurance in the case of two cities. Workmen's compensation acts are in force in these provinces. Some of the cities include compensation charges in their miscellaneous expenses, but do not carry insurance for the same.

Debentures Issues and Sinking Funds

Yearly charges for sinking funds have been figured out in most cities and are paid out of revenue, though in Moose Jaw only a depreciation fund is maintained.

In Winnipeg, standard rates of depreciation are applied to the different parts of the plant. The average rate for the whole system approximating 4 per cent. of the total investment. It was considered unjust to the Winnipeg tax-payers and current-users of the present generation and unduly beneficial to future generations that both sinking fund and depreciation reserve should be provided. The Public Utility Commissioner of Manitoba ordered

that whatever sums are necessary for payment to the sinking funds shall be taken from the depreciation reserve. This sinking fund withdrawal amounts to about 1.8 per cent on the total investment. The balance of about 2.2 per cent is carried as a depreciation reserve for plant replacement. The statements of the municipal department show only a change to depreciation, from which later a transfer is made to the Sinking Fund Trustees appointed by the Judiciary. Hence the depreciation charges in Tables IV and V should really be divided into two portions, one amounting to about eighteen-fortieths being allotted to sinking funds and the balance forming the true depreciation reserve. This method of financing is perfectly sound though it differs somewhat from usual practise.

The investment and use of these sinking funds presents a problem that has received much attention in the West. Some of these funds have been invested in other municipal securities, and in school debentures. Loans have been made on mortgages, while in a few places the money simply draws interest in the banks. In times of depression it would be hard to realize on some of these investments in case this were necessary. There is also the temptation in bad years to fail to set aside the full amount, hoping to make up the deficit at a later date. During depressions it is sometimes impossible to collect all the taxes and in such cases the sinking funds often do not receive their full allotment.

There is necessarily a large element of risk in investments earning high returns and such use of sinking funds should be closely scrutinized. As these funds are public monies, they should only be used in absolutely safe investments.

An innovation in municipal finance has been brought before the public in order to remove these elements of risk incurred with sinking funds. This consists of the substitution of serial debentures for the ordinary long-term debenture with its sinking funds. In the end the cost to the public is the same provided the two bonds can be sold at the same price. In the case of the serial debentures an installment of the principal is paid off each year together with the interest charges on all outstanding bonds for that year. This relieves the municipal councils of the responsibility for sinking fund investment and lifts a considerable burden from their shoulders.

A statement of the case for serial bonds is put very concisely in the following paragraphs from Document 23 of the State of New York's Constitutional Convention.

The most certain, simple and cheap way to amortize a debt is to pay it off in annual installments. The uncertainties of calculation which have so unfortunately affected our sinking funds in the past are at once eliminated. There is no large fund left in the hands of public officials to be cared for and invested and reinvested for fifty years with all the attendant risk and temptation, and the danger that this power of investment in various local securities may be perverted into a political power is entirely removed. Furthermore, the fact that the same administration that incurs a debt must at once begin within a year to make provisions for its retirement, necessarily and strongly tends towards responsibility and prudence in the contraction of the debt.

It has been maintained that investors prefer long-term securities and in consequence the serial debentures could not be marketed at as favorable prices as under present methods. Several prominent Canadian bankers who were consulted regarding serial bonds, expressed the opinion that there would now be practically no difference in placing the serials at as favorable rates as the long-terms.

One leading American banker pointed out that, at the time of writing, short term bonds commanded better prices than long term securities and that he believed serial bonds could sell fully as well if not better than sinking fund securities.

Document 23 of the New York Constitutional Convention may be quoted with interest on this subject. Referring to the marketability of serial bonds, it is stated:

> After careful investigation, however, your committee is of the opinion that serial bonds are quite as marketable as sinking fund bonds. At a recent sale by the Finance Department of New York City, where a sale of serial bonds was made side by side with sinking fund bonds, the former brought when reduced to terms of equivalent maturity, a better price than the latter, the Comptroller of the city attributing the success to the serial bonds. Inquiry among the large financial houses of New York, Boston, Chicago and Philadelphia has developed practically the unanimous opinion of those authorities that serial bonds are at least as marketable as sinking fund bonds. The system has already been adopted by other States of the Union and is also now in use by many of the cities and smaller subdivisions of this State.

There is a strong temptation in the West to adhere to the sinking fund plan, for often the municipalities are able to invest these funds at rates higher than the interest charges on the debentures and thus they relieve their municipalities of a certain amount of taxation. In spite of the element of risk this is often considered very clever administration.

One further objection to the long term bonds, deserves mention here. Such a bond requires only a comparatively small annual sinking fund charge, which is attractive to an uninformed

tax-payer. On the other hand, if an adequate depreciation fund is not set aside to provide replacement of plant at the proper time, owing to the low sinking fund charges, low rates may be quoted at the expense of future consumers. For after the plant has had to be renewed such consumers will not only continue to pay interest and sinking fund charges on the old plant which was worn out by their predecessors and hence is of no benefit to them, but will also have to pay similar charges on debentures that have to be issued to renew the plant. This is unfair discrimination against future consumers.

Attention has already been called to the long life of many of the debentures. It is certain that the plants which these debentures cover, generally cannot last their full terms. At a certain time they will be worn out and have only scrap value or they may become obsolete, yet the original debentures will still be unredeemed. The more equitable and just system is the modern method of limiting the term of the bonds to the life of the improvement they are to cover. This practise is required by law now in several of the American states.

There seems to be a tendency among accountants and some engineers to over-estimate the life of electrical machinery as used to-day. If one considers for a moment, merely the changes brought about in the last fifteen years by the steam turbine in the power plant and by new lamps and fixtures in the art of illumination, and then if one further determines the number of machines bought so long ago that are still economically serviceable in growing cities, it will become apparent that the estimates of the life of the plant made fifteen years ago have been entirely misleading and in error due to obsolescence either from improvement in the art or from inadequacy in capacity. Apparently such progress is not at an end and present-day machinery will be subject to the same influences. It would be well then for municipal authorities to give careful attention to this phase of the situation when deciding on the probable life of their plant and the debentures to cover the same.

The adoption of serial bonds and the adjustment of their maximum term to the life of the improvement they are intended to cover, will provide an equitable and just method of financing future developments. The question naturally arises whether it would be wise or necessary to readjust the present outstanding securities. It has been suggested that these be exchanged for serial bonds properly adjusted to the life of the improvements they cover. But such could only be accomplished with the

consent of the outstanding bondholders. It is probable that this would involve some difficulty on account of the holdings being largely in Europe where any financial innovations would be looked upon with suspicion.

Depreciation and Obsolescence

Probably the most frequent criticism one hears of municipal ownership is that adequate depreciation funds are not set aside. When renewals become necessary, these must be made either at the expense of the taxpayer instead of the consumer who enjoys the utility, or more debentures must be issued. The larger cities of Western Canada are apparently providing suitable depreciation funds which represent the difference between the life of the plant and that of their debentures, so that the combined funds will replace the plant at the end of its usefulness. Investigation tended to show that the credit for this foresight was largely due to the work of competent auditors rather than to the initiative of the municipal councils.

The smaller cities do not seem to maintain this fund and for that reason their surplus has been declared at the expense of future replacement funds. A study of the situation in each of these cities would undoubtedly lead to the establishment of a depreciation fund even at the expense of slightly increased rates.

The question of obsolete machinery presents many difficulties. Most of the cities have outgrown their first electric plants and these have either been scrapped or are virtually obsolete as reserves. In many cases some of the machines now in use will soon be too small and uneconomical if the city continues to grow. Yet practically the whole value of these former plants is covered by debentures on which the present consumers are paying interest and sinking fund charges. The question arises as to how this obsolescence charge shall be financed.

At Edmonton, the capital account for obsolete machinery in the various plants is excessive, as is evident from the high plant values in Tables IV and V. The former Superintendent, R. H. Parsons, made a commendable effort to wipe out as much of this as possible. In 1912 the power plant was granted $100,000 out of general taxation funds for this purpose. The sum of $170,000 was set aside in 1913 from the power plant revenues for depreciation and obsolescence and in 1914 a sum of $87,817.00 was again set aside for a similar purpose. It was hoped that this obsolescence charge would be totally wiped out in 1915.

War conditions, however, made reductions in rates advisable and considerable still remains to be written off the accounts.

In 1913 the auditors recommended a general tax to meet this charge on the basis that the city would be paying for "errors of past years," but this suggestion was not adopted. When this charge for obsolete machinery has been removed either by the retirement of debentures or the replacing of inefficient equipment by modern machinery out of the special depreciation and obsolescence funds, it is estimated that the utility can reduce its charges by about 40 per cent.

An appraisal of the plant at Moose Jaw in 1914 showed a sum of $37,700 unaccounted for out of the debenture issue. It will be necessary in the near future to provide a fund to meet this discrepancy and also to provide for some of the fire losses not covered by insurance.

It therefore seems necessary in certain cases to wipe off at once the charges for obsolete machinery either by general taxation or by funds from current revenue secured by increased rates. The latter plan appears to be the more equitable and just of the two, for those enjoying the utility are then paying all its costs.

Charges for Municipal Lighting and Street Railway Power

The revenues of the electric power utilities are dependent to some extent on the rates charged the city for street lighting and the street railway for power. These rates will now be discussed.

Medicine Hat has no electric street lighting or street railway.

The Lethbridge electrical utility charges the street railway department two cents per kilowatt-hour for power. The city lighting equipment belongs to the electrical utility. The city is charged with all repairs and maintenance on this system and pays for power at the net plant cost, including fixed charges on the lighting systems.

Moose Jaw has a street railway owned by a private corporation and operated by Diesel engines. The municipal power plant charges the city the actual cost of maintenance of its lighting system plus a meter rate of two cents per kw-hr. for arc lamps and $2\frac{1}{2}$ cents per kw-hr. for incandescent lamps.

In Saskatoon the street railway is charged $1\frac{1}{2}$ cents per kw-hr. for the direct current it takes from the switchboard of the electrical plant. The city is charged at the rate of $70.00 per year for its arc lamps while tungsten lamps for street lighting and municipal buildings are charged at the regular rates, viz.: eight cents

for the first 100 kw-hr., seven cents for the next 50 kw-hr. and six cents for all over 150 kw-hr. per month.

At Regina, the city is charged by the utility, $2\frac{1}{4}$ cents per kw-hr. plus a service charge of 50 cents per connected kilowatt per month on 428 kw. for street lighting. This does not include repair and maintenance charges. The street railway pays $1\frac{3}{4}$ cents per kw-hr. for the power used plus a service charge of 50 cents per month per connected kilowatt on 1000 kw. The power is measured on the direct-current terminals leaving the switchboard.

The street railway paid 2 cents per kw-hr. for its power at Edmonton in 1914. For general street lighting the rate is 3.1 cents per kw-hr. plus maintenance and operation cost plus $3\frac{1}{2}$ per cent for departmental charges. The city of Edmonton also pays 5 per cent on capital expenditure for the street lighting system. The city has built a "Whiteway" on Jasper Avenue which is handled differently from the other lighting charges. In this case the charge is 3.1 cents per kw-hr. plus maintenance and operation costs plus $3\frac{1}{2}$ per cent for departmental charges. Two thirds of this gross sum is charged to local improvements as a frontage tax and one third to the city of Edmonton. The city also pays 5 per cent interest on its third of the capital expenditure. The balance of the capital expenditure was charged up to local improvements when the system was built.

Street lighting in Calgary costs a fixed sum per lamp per year. This varies from $65.00 for a magnetite arc lamp to $6.00 for a 16-c. p. incandescent lamp. The street railway pays 1.5 cents per kw-hr. for its power measured on the direct-current wattmeters on the outgoing feeders from the substations.

The street railway at Winnipeg is operated by a private corporation with its own power supply. The city is charged 0.875 cent net per kw-hr. for street lighting and 0.625 cent net per kw-hr. for water pumping, for electrical service from the municipal plant.

There is evidently no uniformity of practise in charging for street lighting and for power used by other utilities. Street lighting usually produces a higher load factor than similar service to private consumers. Water pumping also provides a high load factor and is very desirable service when pumping can be done in off-peak hours. Street railway service on the other hand frequently has no better load factor than other commercial power.

It would therefore seem best to charge for all these services in two parts; first, a demand charge covering the fixed charges of that portion of the plant needed to meet maximum demands,

giving proper consideration to when these occur, and second, a meter rate on all current furnished, which rate would consist of operating and distribution costs together with a certain proportional part of the overhead and management charges.

The Disposal of Surplus

In regard to the disposal of surplus, at Kamloops this was carried to a summary account where it balanced the losses incurred in the operation of other utilities.

The profits were small in the case of Medicine Hat and of Lethbridge and were carried over into current revenue. The surplus of Regina and of Saskatoon are carried over into general revenue accounts where they offset in a measure the deficits incurred in the operation of the municipal street railways.

At Moose Jaw the surplus is transferred to the account for municipal street lighting where it balances two-thirds of the cost of this service. This practise is wrong, for street lighting is a public convenience and necessity to the whole community and should therefore be at the expense of the city as a whole. The costs of such service should be included in the general taxes just the same as the cost of sewage disposal, fire and police protection.

Calgary had a total surplus reserve of $154,850.91 set aside by the end of 1914. No purpose has been allotted to the reserve up to the present time. Rates were reduced in 1915 and in consequence it is probable that the surplus for that year will be small.

Edmonton's surplus as already explained consists of the following items:

Power plant's net surplus....................	$ 828.33
Reserve set aside by By-Law No. 576..........	12,481.62
Waterworks charges taken out of electric revenue	11,202.97
Surplus in distribution dept..................	55,190.95
Net Surplus..............................	$79,703.87

Of this amount the waterworks charges should be assumed by the water department by increased rates. The distribution department has now a total surplus reserve of $104,682.47. This has been distributed as follows:

Deficit of Strathcona........................	$6,554.49
Obsolescence Reserve........................	15,000.00
Reserve for Underground Construction.........	83,127.98

It seems hard to justify the use of this surplus for underground construction when the funds are taken from current revenue. This is a case where permanent improvements are being made out of the receipts from current lighting and power rates.

At the beginning of the fiscal year Winnipeg had a deficit of $81,409.89 remaining from a total deficit of $142,273.64 incurred during the first two years of operation. The surplus for the current year was applied to this account reducing the net deficit on April 30th, 1915, to $2,725.17, which will probably be wiped out this year and permit lower rates to be quoted to customers.

The variations in practise as set forth in the preceding paragraphs raises the question as to the proper disposal of surplus. The municipalities argue that the utilities are theirs, that they have earned profits which belong therefore to the community, and the city through its governing board can dispose of this surplus as it deems proper.

However, if the situation is analyzed carefully certain facts will be revealed which raise questions as to the equity of the above practise. In the first place these profits accrue out of rates paid by the consumers of light and power and they are therefore paying in their rates more than it is costing the city to provide such service. Suppose such profits are used, as is frequently the case, to make good a deficit in another department, say in the water department, then the consumers of water are paying rates that are lower than the city's gross cost for supplying water. One is then confronted with this situation ,that the electric light users pay a portion of the cost of the water consumer's service. The injustice of this condition is at once apparent. The same reasoning applies in regard to balancing street railway deficits by surplus funds.

On the other hand if the surplus is carried to a general revenue account, and is used to defray the current expenditures of the city or to meet specific civic costs, such as street lighting, it virtually takes the place of additional taxes. Then the electrical consumers are paying a portion of the city's general taxes in addition to the cost of supplying them with power and light. This is neither fair nor just if the utility has already paid taxes on its valuation. If it has not been taxed, then there is a considerable measure of justification for this practise.

Reference has already been made to the practise at Edmonton of utilizing the surplus for permanent improvements. In general when such funds are used either to replace old equipment, to extend the utility or to make permanent improvements in the system, the benefits of such will be enjoyed by future consumers extending over a period of years. They alone should bear the costs of such improvements and it is therefore unjust to levy

high rates on present consumers that provide funds for improvements they do not enjoy when paying those rates.

In cities where a proper depreciation and obsolescence fund has not been provided, it would seem necessary to set aside at once all surplus funds in a special sinking fund to make up for failures in the past to provide for this cost.

How then should the surplus be used? In every power plant there are at times emergencies that call for expenditures in excess of the current costs of other periods, such for instance as damages to the system from sleet storms, lightning, floods and fires. It would seem reasonable therefore that a special reserve fund of moderate amount should be set aside for this purpose out of the profits earned.

The use of surplus to provide for deficient depreciation funds has been pointed out. This procedure is so reasonable and rational that no argument need be presented to justify it, for sooner or later such funds must be forthcoming and rightly should be provided by the users of the utility.

When profits exceed reasonable allowances for the two preceding purposes, then the consumers are entitled either to a proportional rebate on their bills or to reduced rates for the following year. The former method has certain psychological advantages as it emphasizes the cooperative features of the enterprise and the mutual profit and loss characteristics of municipal undertakings, and also obviates the political pressure brought to bear on officials when rate changes are to be made.

If rates were reduced in proportion to surplus, the reductions would amount to from 7 to 15 per cent in the different cities, with the exception of Medicine Hat and Lethbridge.

Table VI contains some interesting deductions from Table V. Winnipeg figures are for the municipal plant only and do not include the large private corporation operating the street railway and also selling light and power in the city.

The plant equipment per 1000 inhabitants averages nearly twice that of the average of nineteen cities in Massachusetts. The electrical consumption per inhabitant is more than twice the eastern average.

The average of kw-hr. generated per kilowatt capacity of plant for the Canadian cities amounts to 1457 kw-hr. This indicates that practically the same station load per kilowatt installed exists in the West as in the Massachusetts cities. The equivalent coal per kw-hr. was figured from the cost of coal per ton of 2000 pounds and the fuel cost per kw-hr. as given in Table

TABLE VI.—GENERAL DATA ON PLANT OPERATION.

City	Plant capacity per 1000 inhabitants kw.	Debenture issue per inhabitant	Kw-hours generated per year per inhabitant	Kw-hours generated per year per kw. of plant capacity	Pounds of coal per kw-hour	Operating cost less fuel per kw-hour	Distribution cost per kw-hour	Overhead costs less taxes per kw-hour	Production cost less fuel and taxes per kw-hour	Fixed charges per kw-hour	Net Cost less fuel and taxes per kw-hour
Kamloops	491	$96.45	478	973	5.48	0.576	0.069	0.190	0.835	0.547	1.382
Medicine Hat	333	47.77	339	1016	....	0.417	0.109	0.117	0.647	0.912	1.559
Lethbridge	230	68.96	341	1484	6.25	0.753	0.254	0.275	1.282	1.351	2.633
Moose Jaw	150	35.39	187	1247	7.64	0.712	0.572	0.351	1.730	1.398	3.128
Saskatoon	238	41.91	388	1491	4.11	0.530	0.199	0.219	0.948	1.088	2.036
Regina	190	37.16	233	1226	5.23	0.582	0.272	0.181	0.982	0.874	1.856
Edmonton	205	56.60	438	2139	4.68	0.658	0.158	0.228	1.078	1.284	2.362
Calgary A	142	25.36	392	....	....	....	....	....	1.179	0.525	1.704
Calgary B	167	....	478	....	....	....	....	....	....	..	....
Winnipeg	150	35.92	312	2083	....	0.127	0.073	0.143	0.508	0.912	1.420
Average of 19 cities in Massachusetts	113	....	165	1462	3.12	0.338	0.423	0.344	1.252	....	....

" Calgary A " refers to the municipal plant only.

" Calgary B " includes the private corporation which has a franchise in the city. It has a plant of 2000-kw. capacity and delivers about 2,000,000 kw-hr. per year.

V. The Lethbridge plant consumes the whole output of its mine without much hand picking of the coal. The coal is rather low grade and high in ash. Hence the fuel consumption is apparently excessive.

The high coal consumption of Moose Jaw together with other high production costs is due in a large measure to the fact that half the boiler room was under construction during the financial year 1914.

Considerable high grade Pennsylvania coal was burned during the year at Saskatoon which partially accounts for the low coal consumption. A survey of these figures on coal indicates that power costs can be considerably reduced by improved plant

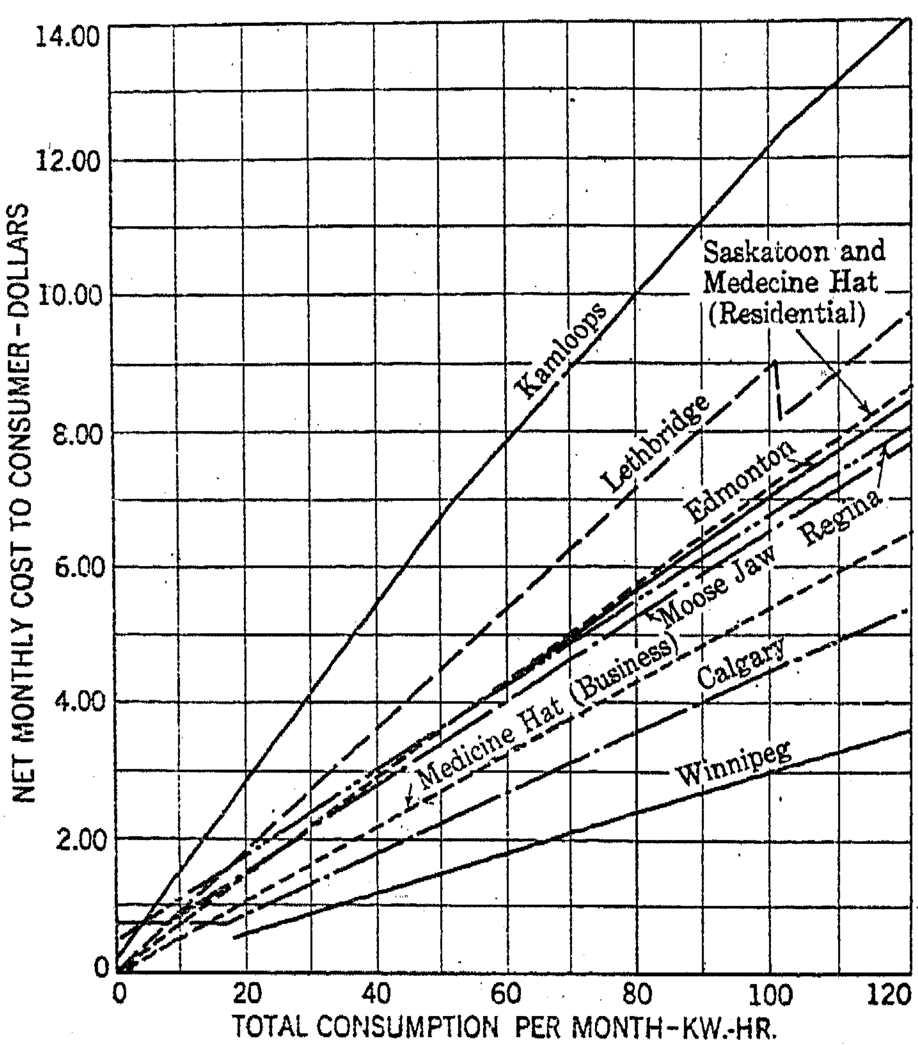


FIG. 2—MONTHLY LIGHTING CHARGES TO SMALL CONSUMERS

operation. The cost of fuel per kilowatt varies widely as shown in Table V. This item in the total cost was therefore eliminated from the figures given in Table VI in order that a more equitable basis of comparison might be obtained.

The column of "operating costs less fuel charges" indicates very clearly the influence of the high labor costs due to higher wages in the west as compared with those of the Massachusetts cities. Cheaper service may be expected then by reducing labor costs per unit of output as well as cutting down fuel costs.

Western distribution costs with the exception of Moose Jaw are generally low, possibly because the systems are comparatively new and have not needed extensive repairs. The item of taxes

was also omitted from the costs presented in Table VI as there was no uniformity of practise in regard to this charge. The office and management costs of these western utilities are low compared to the Massachusetts costs.

The average production cost less fuel and taxes is 1.021 cents per kw-hr. for the western cities against 1.252 cents per kw-hr. in the Massachusetts cities. The average fixed charges of the Canadian cities are 0.988 cent per kw-hr. or nearly the same as the production cost without fuel or taxes. The average net cost without fuel or taxes amounts to 2.009 cents per kw-hr. From Table V the average net cost including fuel and taxes is 2.793 cents per kw-hr.

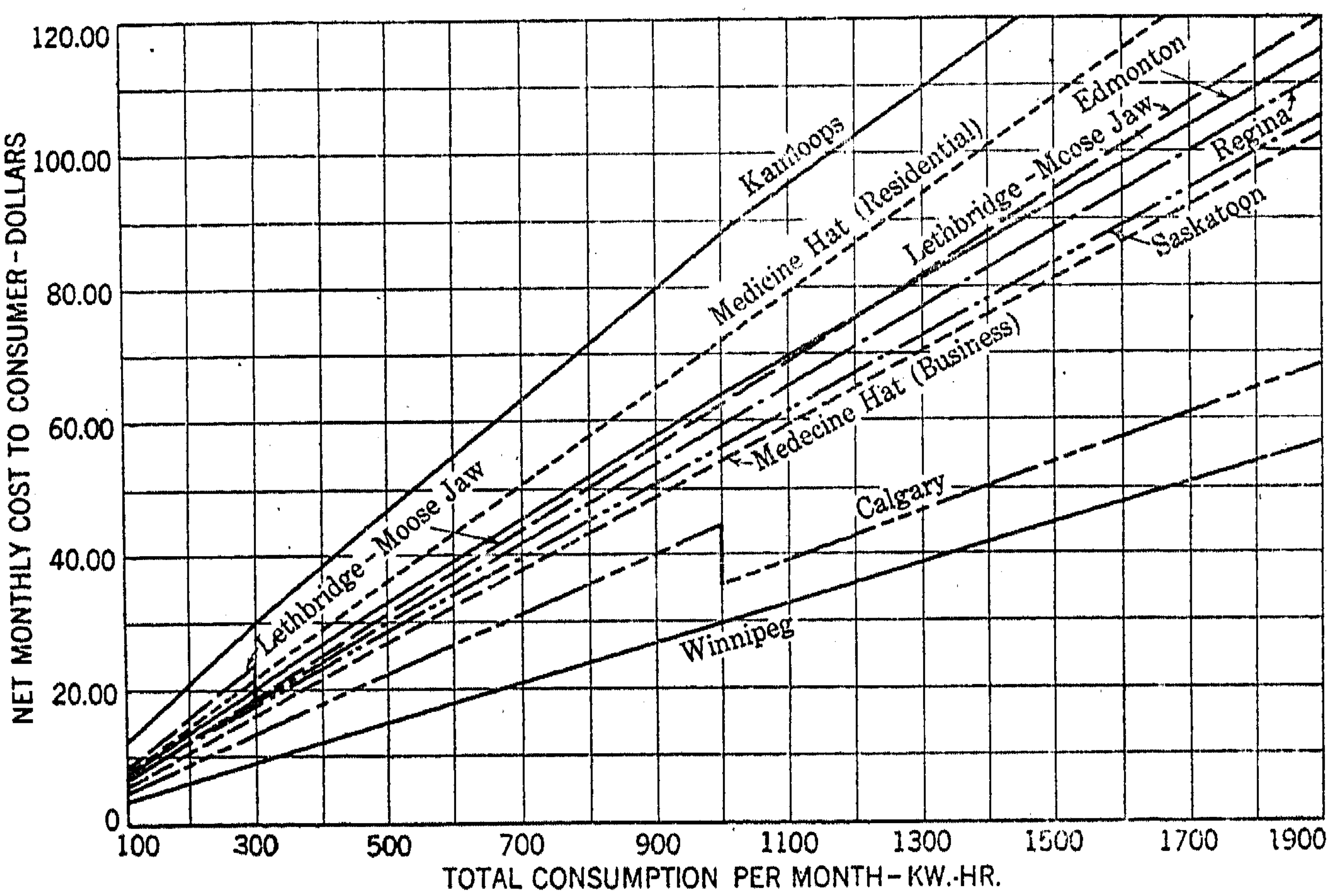


FIG. 3—MONTHLY LIGHTING COSTS TO LARGE CONSUMERS

RATES FOR LIGHT AND POWER SERVICE

The rates for lighting and power with the prompt payment discounts in the various cities are given in Tables VII and VIII, and are shown graphically in Figs. 2, 3, 4 and 5. These curves are plotted with total kilowatt-hours consumption per month per consumer as one ordinate while the other indicates the net monthly cost to the consumer when he avails himself of the prompt payment discounts. Comparison can be made between the different cities by selecting any given consumption and noting from the curves the net cost in each city. Rates of other cities can be compared by figuring the net cost of a given electrical consumption and comparing it with the charges in the Western plants as shown by the curves.

The curves showing the lighting rates for Regina for large consumers are not absolutely correct for they do not include the service charge of 50 cents per kilowatt of connected load. As no data are at hand in this case regarding the relation of connected load to consumption, it was impossible to plot curves representing true conditions. The actual cost can be found by adding the service charge to the figures given by the curves. The curve for charges to small consumers has been plotted on the assumption of one kw. connected load per customer, and may thus be slightly in error for any particular case. No attempt was made to show the two meter rates of Moose Jaw and other places.

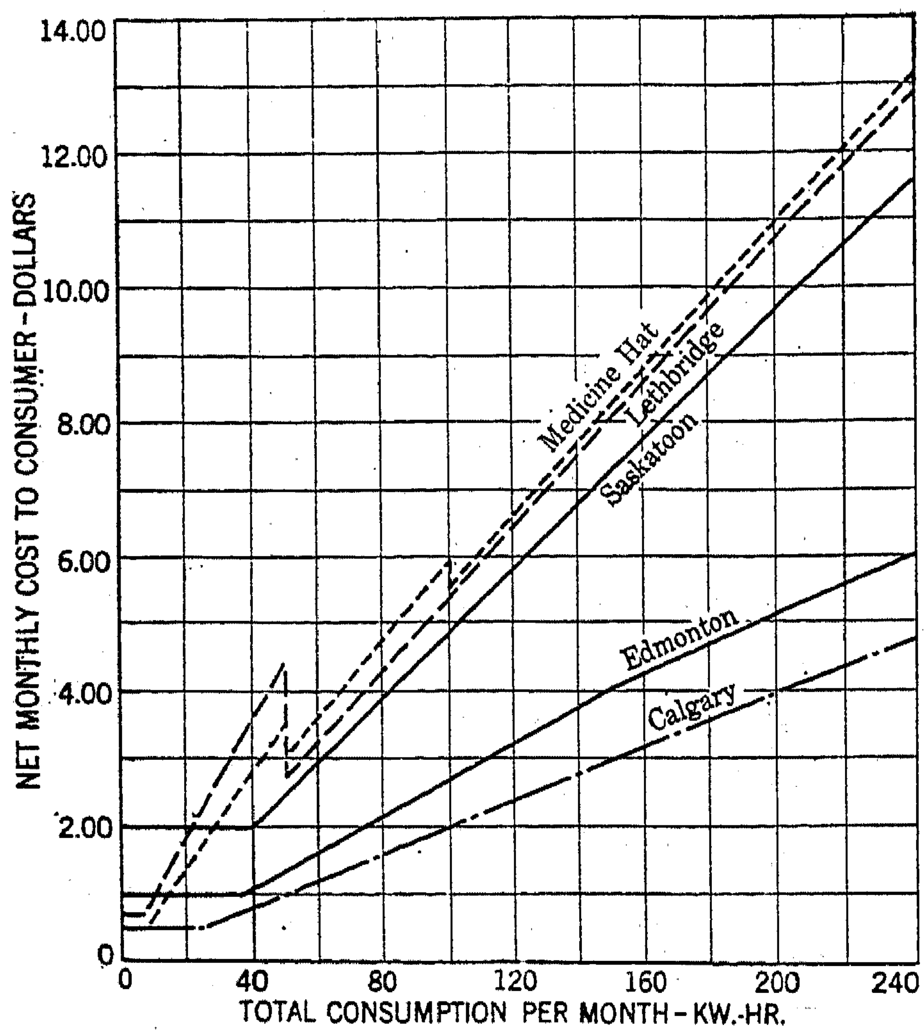


FIG. 4—MONTHLY POWER COSTS TO SMALL CONSUMERS

The effect of the general use of natural gas for domestic lighting and of the effort to build up a large power load is shown in the high domestic lighting rates at Medicine Hat.

A service charge of 50 cents per month per kilowatt of demand is charged at Regina against the customer. It is maintained that this covers the so-called "customer charge" consisting of the costs of reading meters, billing, etc., and also a portion of the demand charge on the plant which consists of the charges on capital to maintain capacity in the station ready to serve customers. Flat rates are also still in existence in some cities.

Medicine Hat, Lethbridge and Calgary charge for light and

power on a "sliding scale" basis, as shown in Figs. 3 and 5. In order to show the unfairness of rates charged on this basis take for example the Medicine Hat rates to two consumers using respectively 645 and 655 kw-hr. per month. The charges, are as follows:

1st consumer	645 kw-hr.	..	$4\frac{1}{2}$	=	\$29.02
2nd "	655	"	4	=	26.20

The second consumer uses 10 kw-hr. more than the first consumer yet actually pays \$2.82 less for his total power. No analysis of costs could possibly justify such a practise, for the smaller consumer is manifestly discriminated against.

It has been pointed out that the large consumer is entitled

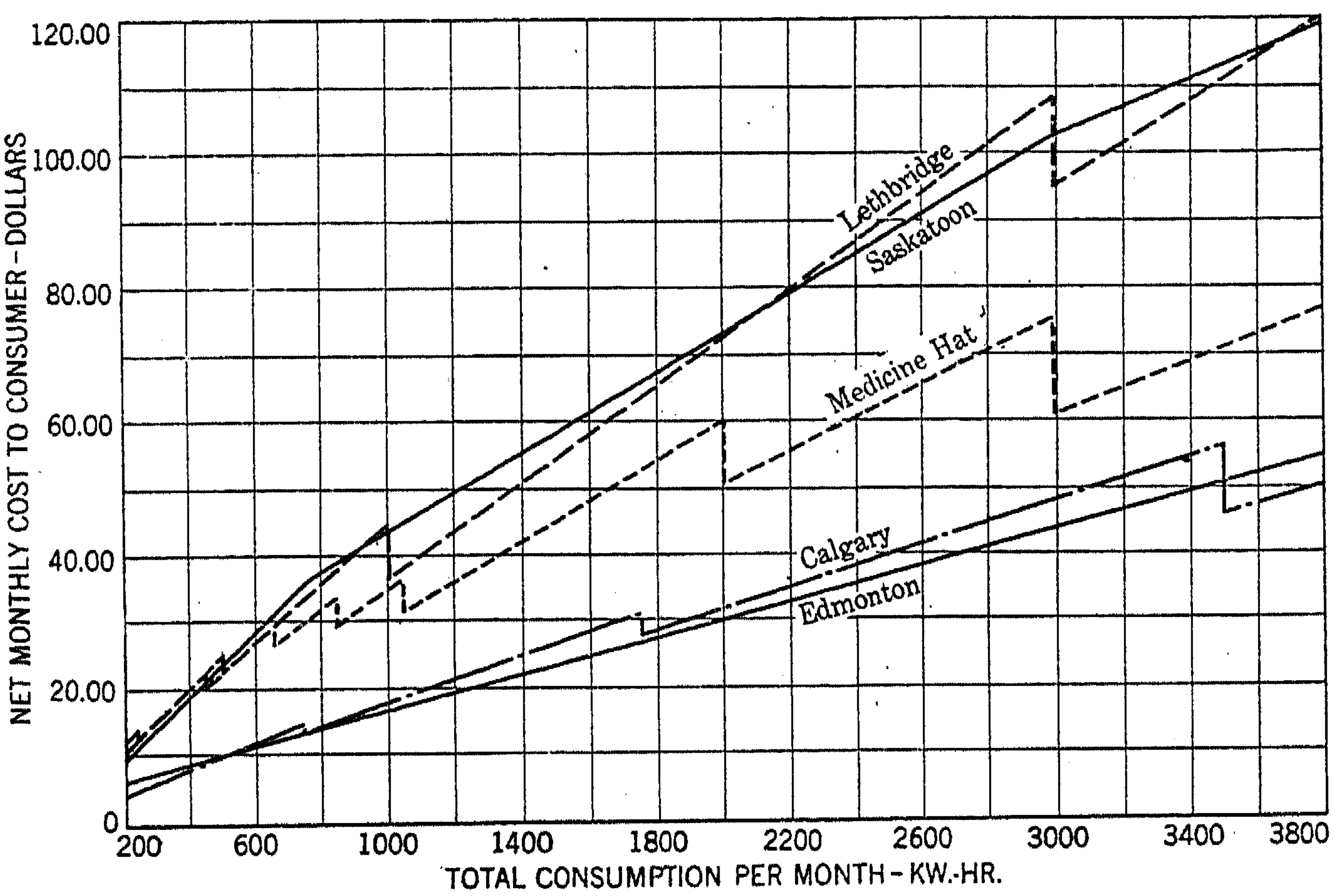


FIG. 5—MONTHLY POWER COSTS TO LARGE CONSUMERS

to some consideration in rates but these should be adjusted to the cost of service. Hence if an analysis of costs justifies the Medicine Hat rate of say $4\frac{1}{4}$ cents per kw-hr. for the first 650 kw-hr. per month, then the consumer should pay that amount regardless of his total consumption. If, however, additional power over 650 kw-hr. can be provided to one customer at a lower cost than $4\frac{1}{2}$ cents per kw-hr. then the consumer is entitled to a correspondingly lower rate for his consumption over and above the first 650 kw-hr. only.

General cost curves could not be plotted from the power rates given in Table VIII for the cities of Kamloops, Regina, Moose Jaw and Winnipeg.

TABLE VII.—RATES FOR LIGHTING.

KAMLOOPS.

Population 5500. kw-hr. generated 2,628,100

Flat Rate	10 c. p.	16 c. p.
Each light per month (not to exceed two lights)	1.25	2.00

Discount if paid within 10 days—20%.

Meter Rate.

First 50 kw-hr.	14 cents per kw-hr.
Next 50 "	12 " " "
Next 200 "	10 " " "
Next 700 "	9 " " "
Over 1000 "	8 " " "

1 cent per kw-hr. discount will be allowed if paid within 10 days from date due.

Meter rent 25 cents per month.

MEDICINE HAT

Population 9000. kw-hr. generated 3,050,070.

Private residential lighting	8 cents per kw-hr.
Business lighting	6 " " "

10% discount on bills paid in 10 days.

LETHBRIDGE

Population 10,000. kw-hr. generated, 3,415,000.

Up to 100 kw-hr. per month	10 cents per kw-hr.
101 to 300 " " "	9 " " "
301 to 600 " " "	8 " " "
Above 601 " " "	7 " " "

10 per cent discount on bills paid in 10 days.

MOOSE JAW

Population 20,000. kw-hr. generated 3,739,990.

Lighting Rate	7 cents per kw-hr.
Meter Rental	25 " " month
Minimum charge	75 " " "

10 per cent discount on bills paid in 10 days.

Customers may also use two-rate meters on which a charge of only 3 cents per kw-hr. is made for light, heating, cooking and small motors during off-peak hours.

Meter Rental	25 cents per month
Minimum charge	3.00 per month.

10 per cent discount on bills up to $40, paid in 10 days.

15 per cent discount on bills over $40, paid in 10 days.

SASKATOON.

Population 25,000. kw-hr. generated 8,873,642.

First 100 kw-hr. per month	8 cents per kw-hr.
Next 50 " " " "	7 " " "
All over 150 " " "	6 " " "

Minimum monthly charge $1.00.

10 per cent discount on bills paid in 10 days.

REGINA.

Population 40,000. kw-hr. generated 9,315,355.

First 300 kw-hr. per month	7 cents per kw-hr.
All over 300 " " "	6 " " "

Service charge 50 cents per kw. of demand.

Burned out lamps renewed by city free of charge.

10 per cent discount on bills paid in 10 days.

Special discounts for large lighting consumption.

EDMONTON

Population 50,000. kw-hr. generated 21,927,089.

1 to 100 kw-hr. per month	$7\frac{1}{2}$	cents per kw-hr
101 to 400 " " "	7	" " "
401 to 1000 " " "	$6\frac{1}{2}$	" " "
1001 to 2200 " " "	6	" " "
All over 2201 " " "	$5\frac{1}{2}$	" " "

Minimum monthly charge 75 cents.

No discounts allowed on accounts less than $1.00.

5 per cent discount on bills paid in 10 days.

The following schedule cover the charges for sign lighting:

1 to 375 kw-hr. per month	5	cents per kw-hr.
376 to 5000 " " "	3	" " "
All over 5001 " " "	2	" " "

A schedule of minimum charges per kw. of connected load for each month of the year has also been prepared but is not quoted in this paper.

10 per cent discount allowed on bills paid in 10 days.

CALGARY.

Population 80,000. kw-hr. generated 31,391,596.

First 1000 kw-hr. per month	5	cents per kw-hr.
All above 1000 " " "	4	" " "

Minimum charge 75 cents for the first kw. of connected load and 50 cents for each additional kw. of connected load.

10 per cent discount on bills paid in 10 days.

WINNIPEG.

Population 200,000. kw-hr. delivered at city terminal 62,493,162.

Domestic lighting...$3\frac{1}{2}$ cents per kw-hr.

Minimum monthly charge of 50 cents per meter.

10 per cent discount on bills paid in 10 days.

Commercial lighting sells at the same rate but with a net minimum monthly payment of $1.00 per kw. of connected load and subject to certain wholesale discounts for large consumption not quoted.

TABLE VIII.—POWER RATES.

KAMLOOPS.

Population 5,500. kw-hr. generated 2,628,100.

Five classes of power rates are in effect, A for small motors; B for medium sized motors; C for large motors; D for irrigation pumping and E for heating and cooking off-peak.

Class A Power.

$6 per h. p. per year plus

First 50 kw-hr.	6	cents per kw-hr.
Next 100 "	4	" " "
All over 150 and under 500 kw-hr.	3	" " "

Class B Power.

$6 per h. p. per year plus

First 500 kw-hr.	$3\frac{1}{2}$	cents per kw-hr.
Next 1000 "	2	" " "
Over 1500 and under 2500 kw-hr.	$2\frac{1}{2}$	" " "

Class C Power.

$6 per h. p. per year plus

First 2,500 kw-hr.	3	cents per kw-hr
Next 4,000 "	$2\frac{1}{2}$	" " "
Next 5,000 "	2	" " "
Next 10,000 "	$1\frac{1}{2}$	" " "
All over 21,500 "	$1\frac{1}{4}$	" " "

Class D. Irrigating only.

First	2500 kw-hr.	2½	cents per kw-hr.
Next	2500 "	2	" " "
All over 5000	"	1½	" " "

Class E. Heating and Cooking.

Off-peak load....3 cents per kw-hr.

Meter rent for all classes, 25 cents per month.

10 per cent discount on bills paid in 10 days.

MEDICINE HAT.

Population 9000. kw-hr. generated 3,050,070.

50 to 100 kw-hr. per month	6	cents per kw-hr.
101 to 250 " " "	5½	" " "
251 to 450 " " "	5	" " "
451 to 650 " " "	4½	" " "
651 to 850 " " "	4	" " "
851 to 1,050 " " "	3½	" " "
1051 to 2,000 " " "	3	" " "
2001 to 3,000 " " "	2½	" " "
3001 to 5,000 " " "	2	" " "
5001 to 25,000 " " "	1½	" " "
Over 25,000 " " "	1	" " "

Minimum charges, $1.00 per month per h. p., single-phase motors.

$.50 per month per h. p. three-phase motors.

The following discounts are allowed on bills for prompt payment.

For the first $100	per month consumption			no discount:
For the second $100	" " "	excess over	$100	10 per cent.
For the third $100	" " "	" "	$200	20 "
For the fourth $100	" " "	" "	$300	30 "
For the fifth $100	" " "	" "	$400	40 "
From $500 to $1000	" " "	" "	$500	50 "
Excess over $1000	" " "	" "		60 "

LETHBRIDGE.

Population 10,000. kw-hr. generated 3,415,000

There are three schedules in force, the Peak, the Off-Peak and the Flat Rates.

PEAK SCHEDULE.

Up to 50 kw-hr. per month	10	cents per kw-hr.
50 to 250 " " "	6	" " "
251 to 500 " " "	5½	" " "
501 to 1000 " " "	5	" " "
1001 to 3000 " " "	4	" " "
Over 3000 " " "	3½	" " "

OFF-PEAK SCHEDULE.

Up to 100 kw-hr. per month	10	cents per kw-hr.
100 to 500 " " "	5	" " "
501 to 1000 " " "	4	" " "
1001 to 3000 " " "	3	" " "
Over 3000 " " "	2	" " "

10 per cent discount on bills paid in 10 days.

To obtain these off-peak rates the consumer must install a time switch which will be under the control of the city and be adjusted by the city to conform to the following hours. Between the hours of 1 a.m. and 6 p.m. from February 1st to December 1st.
" " " " 1 a.m. and 4.30 p.m. from December 1st to February 1st.

FLAT RATES.

These are quoted only for large sizes of motors and for use during off-peak hours and are not given here.

MOOSE JAW

Population 20,000. kw-hr. generated 3,739,990.

Horser power of motors or peak load	Fixed charges per h. p. per month or per h.p. of maximum demand	Meter rate per kw-hr. of consumption
1 to 3	$1.00	3.5
4 to 10	1.00	3.0
11 to 25	1.00	2.5
26 to 50	1.00	2.0
50 to 100	1.00	1.5
Over 100	1.00	1.25

Total charge equals fixed charge plus meter charge.

All charges are classified as follows:

Class "A"—24 hours	unrestricted use	100 per cent of base rate.
" "B"—24 "	restricted "	90 " " " "
" "C"—10 "	unrestricted "	90 " " " "
" "D" 10 "	restricted "	66.6 " " " "

The restricted hours are as follows:

October 15th to October 31st	5.30 to 6.30 p. m.
November 1st to November 30th	5.00 to 6.30 p. .m
December 1st to January 15th	4.30 to 6.30 p. m.
January 15th to February 16th	5.00 to 6.30 p. m.
February 16th to March 1st	5.30 to 6.30 p. m.

10 per cent discount on bills paid in 10 days.

SASKATOON.

Population 25,000. kw-hr. generated 8,873,642.

First	750 kw-hr. per month	5.4 cents per kw-hr.
Next	2250 " " "	3.25 " " "
Next	1000 " " "	2.34 " " "
Balance over 4000	" " "	2 " " "
Domestic power		4 " " "
Minimum charge		$2.00 per month.

10 per cent discount on bills paid in 10 days.

REGINA.

Population 40,000. kw-hr. generated 9,315,355.

First	300 kw-hr. per month	5 cents per kw-hr.
Second	300 " " "	4 " " "
Third	300 " " "	3½ " " "
All in excess of 900 per month		3 " " "

Service charge of 50 cents per month per kw. of demand.

The city uses two-rate meters on which the off-peak rates are as follows:

First	1000 kw-hr. per month	3 cents per kw-hr.
Second	1000 " " "	2½ " " "
All in excess of 2000	" " "	2 " " "

The restricted hours are 6 p. m. to midnight from April 1st to September 30th, from 5 p.m. to midnight during March and October and from 4 p. m. to midnight from November 1st to February 28th.

10 per cent discount on bills paid in 10 days.

EDMONTON.

Population 50,000. kw-hr. generated 21,927,089.

Domestic power not used for commercial purposes costs 4 cents per kw-hr.

Minimum charge 50 cents per kw. of connected load.

General Power Rates.

First	150 kw-hr. per month	3 cents per kw-hr.
151 to	300 " " "	2½ " " "
301 to	5000 " " "	1½ " " "
All over 5000	" " "	1 " " "

10 per cent discount on bills paid in 10 days.

The minimum monthly charges are as follows:

(a) Heating or apparatus other than motors, 50 cents per kw. of connected load.
(b) Single-phase motors up to 3 h. p., 50 cents per h. p. of connected load.
(c) Single-phase motors above 3 h. p., 25 cents per month per h. p. of connected load.
(d) Three-phase motors, 25 cents per h. p. of connected load.

In (a) and (b) the minimum monthly charge is $1.00.
In (c) and (d) the minimum monthly charge is $2.25.

Stand-by Service.

A minimum charge of $1.00 per kw. of connected load per month is made for this service No service is supplied for less than 25 kw. of demand.

CALGARY.

Population 80,000. kw-hr. generated 31,391,596.

1 to 750	kw-hr. per month	2	cents per kw-hr.
751 to 1,750	" " "	1.8	" " "
1751 to 3,500	" " "	1.6	" " "
3501 to 12,500	" " "	1.3	" " "
All above 12,500	" " "	1.1	" " "

A minimum charge of 50 cents per month per h. p. of connected load is made.

When the current is used during off-peak hours only and the amount of current exceeds 130 kw-hr. per connected h. p. per month, the following discounts are allowed:
5 per cent discount for consumptions of 130 to 250 kw-hr. per connected h. p. per month.
10 per cent discount for consumptions of 251 to 300 kw-hr. per connected h.p. per month.
15 per cent discount for consumptions over 300 kw-hr. per connected h. p. per month.

WINNIPEG.

Population 200,000. kw-hr. delivered at city terminals, 62,493,162.

Electric service heating, 1 per cent per kw-hr.

Alternating-Current Power Rates.

The first	50	hours use per month of total connected load	$3\frac{1}{3}$c. per kw-hr.
"	50	" " " " " " " "	2.5c. " "
" "	50	" " " " " " " "	1.9 " "
" "	50	" " " " " " " "	1.4c. " "
" "	50	" " " " " " " "	1.1c. " "
Excess over	250	" " " " " " " "	0.8c. " "

Minimum monthly payment, 75 cents per h. p. of total connected load.

Prompt payment discounts 1 year contracts	10 per cent.
3 " "	15 "
5 " "	20 "

All the above rates are subject to the following wholesale discounts:

For the first $100 per month consumption		no discount.	
" " second $100 " " "	excess over $100	10 per cent.	
" " third $100 " " "	" " $200	20 "	
" " fourth $100 " " "	" " $300	30 "	
" " fifth $100 " " "	" " $400	40 "	
From $500 to $1000 per month consumption	" " $500	50 "	
Excess over $1000 per month consumption	" "	60 "	

The first three charge a fixed sum per h. p. or per kw. connected per month, plus a power consumption charge. Winnipeg has a system of charges based on hours of demand. However, if plotted, the power rates of Regina would be nearly the same as those of Saskatoon, while Moose Jaw rates would likely fall

between Saskatoon and Edmonton as shown in Figs. 4 and 5. The off-peak schedules of the different cities were not plotted.

The Kamloops power rates could not be easily plotted.

These rates were plotted in curve form, not particularly to show absolute values, but to show how size of plant, cheap hydro-electric power and cheap fuel affect the cost of power to the consumer. Low first costs of plant and low fixed charges have an appreciable effect as can be seen by comparing these curves with the figures given in Tables V and VI.

The rates for Calgary are the lowest in the West with the exception of Winnipeg, due largely to the low cost of hydro-electric power.

The Medicine Hat plant serves power consumers almost entirely and its lighting rates are therefore high.

Edmonton rates should be reduced when the obsolescence charges are fully met.

Reductions may be expected in the rates of the other cities in proportion to the growth of the plant load, (for all of the power plants are now operating under normal loads) and with improvement of their load factors.

A comparison of Tables V and VIII shows that in many cities rates for power are quoted at less than net cost and often at less than production cost. It is held that power loads are necessary to build up the load factor and to increase the total output of the plant. In this way the cost per unit will be reduced. On the other hand, it is evident that if such consumers do not pay their proportion per unit, of the fixed charges and other costs, then other consumers—generally those using lighting only—are forced to pay an unduly large proportion of the costs if the utility is to meet its expenses. In such cases there is discrimination in favor of the large power users, who enjoy special privileges at the expense of the smaller consumers. This is unjust and the public can demand that this practise be stopped.

Another argument is that a low rate is quoted by the city as an inducement to industries to locate in its limits. It is maintained that any loss resulting from this low rate is more than offset by the benefits the city receives from having such an industry in its boundaries. This in the abstract amounts to a bonus to such an industry. The injustice of this plan lies in the fact that only the consumers of electricity pay this bonus, which logically should be paid in taxes by all the property owners if the municipality desires to give such aid to an industry.

But on the other hand, the costs of service, of meter readings and of office work are much less in the case of the large consumer than where the demand is small, and it is perfectly reasonable that he should be quoted a lower rate on these grounds. Nevertheless it is difficult to justify rates that do not cover the total operating costs plus fixed charges plus a portion at least of the distribution and office expenses. If the rates are based on service charges, it is proper for the large consumer to pay an equitable share of capital charges for his maximum demand on the station just the same as in the case of the smaller user.

The Winnipeg power rates deserve notice. The base rate does not vary with the size of the electrical demand, but varies with the duration of this demand per month. The logic of this rate is sound for it is evident that no consumer using power for over 50 hours per month could have this all on during the peak load hours. Thus a consumer using all his power for 200 hours per month provides a load two-thirds of which under any circumstances, must occur during off-peak hours. The large consumer only benefits by the liberal discounts given along with the rates.

The primary lighting rates in these Canadian cities have apparently been adjusted to favor the small consumer. The distance from oil-producing territory makes kerosene an expensive commodity. Hence in many cities, even the smallest householders find it not only more convenient but more economical to use municipal electric light than to burn kerosene lamps and these consumers, especially in those cities with minimum charges, provide a very considerable portion of the total revenue. In general the primary rates of cities in the United States exceed those of cities of similar size in Western Canada. Only a complete investigation by a public utility commission would show whether or not the small consumers are unduly favored in the latter cities.

A survey of the rates of privately owned plants in cities of similar size in Wisconsin as reported by the Railroad Commission of that state and in Massachusetts as reported by the Board of Gas and Electric Light Commissioners, indicates that in general their rates are considerably higher both for light and power than in the municipality owned utilities of these Canadian cities.

While it is possible, as already pointed out, that in some of these municipal undertakings adequate provision is not made for depreciation and obsolescence, in most cases this could be provided out of surplus without appreciably affecting rates. Why

then should the Canadian cities be able to provide such rates? In the first place these utilities have no promotion or franchise expenses to capitalize and on which to earn a return. Nor have they capitalized "going value" or "good-will." In these particulars they have a decided advantage over the cities with privately owned plants.

Another feature is that in adjusting rates in privately owned plants, present value must necessarily be considered. In a growing city, property increases rapidly in value and a private company is rightly entitled to earn money on the present value of its holdings or otherwise it would not pay the company to retain the property. In municipal enterprises any increment in value belongs to the city and does not need to be capitalized for rate making, although increasing the available assets of the utility and thus proving of value in issuing securities.

A third factor is the matter of returns on the investment. The Wisconsin Commission has ruled that companies are entitled to rates of from 7 to 8 per cent on their investment in order that capital may be induced to invest in them.

The Board of Gas and Electric Light Commissioners of Massachusetts report for 1914, dividends in privately operated electrical utilities ranging from 5 to 22 per cent. It is probable that those earning the biggest dividends are undercapitalized or that the plant has been largely built out of earnings.

The Canadian municipally-operated utilities are financed by debentures bearing from 4½ to 6 per cent interest. It is at once evident that there is an appreciable saving in this method of financing over that of private companies. This saving results in correspondingly lower rates to the customers of these utilities.

Finally the municipally owned utilities do not require a set of directors and higher officials who often draw extravagant salaries taken from earnings. The executive administration of these utilities is generally quite simple and efficient, the only high-salaried officials being the commissioner, the superintendent and the electrical engineer. Furthermore, it is not possible to milk the municipal utility for exorbitant fees for promotion and legal purposes and for receiverships and reorganizations. There is also no chance to manipulate earnings by means of subsidiary companies who supply power, own roadbeds or have other favorable concessions that enable them to take the cream from the profits of the utility itself.

Central Heating Systems

In the prairie provinces heat and pure water for cities are absolute necessities, the first to permit existence in cold weather, the second on account of the pollution of much of the local water with alkali or river mud. Light is less necessary than the other two. The people of these cities have cooperated in the establishment of their municpal plants to supply light and water but aside from the natural gas supply at Medicine Hat, have taken no steps to cooperate in the economical generation and distribution of heat. They do not seem to appreciate at full value the ease with which such a central heating system can be installed and operated, and the satisfactory financial and economic results that would be obtained from it. However, it must be kept in mind that a large portion of the population emigrated from Europe where such cooperative methods of heating are unknown. Hence this system is not understood and its full value has not been appreciated.

Hence none of these municipal plants has made any attempt to develop exhaust steam central heating in connection with its power plant. This would appear to be a promising field to exploit in those cities where coal is expensive and the winters long and cold, as in Saskatchewan. Where the power plant is centrally located, it should not be a difficult proposition to build tunnels at least through the business section for steam pipes, electric wiring, etc. and to derive a very profitable return therefrom. It should be possible to provide heat to consumers at a lower cost than by present methods. The conditions at Saskatoon seem to be favorable for this purpose as the old reciprocating engine could supply much of the exhaust steam needed. The old station at Regina could also be utilized for similar purposes and need operate only during the heating season.

General Remarks

The municipal electric light and power utilities of these Western cities have on the whole been run efficiently. Their rates are in general fair and reasonable and compare very favorably with those existing in cities of the same size in the United States where private corporations have control.

The public in these Western cities takes a great interest in all utilities and this in a large measure has made them keep up-to-date in equipment and organization. The economic effects of the low rates have not become apparent largely because the real

estate booms and inflated land values have offset the benefits of these rates.

Mistakes have been made in the past in the location and construction of electrical plants and in the selection of machinery. Most cities now have comprehensive plans prepared for plant extensions and only radical changes in prime mover designs would seriously interfere with carrying these out. The introduction and development of the steam turbine was such a change. At present, however, it does not seem likely that another new form of prime mover will be produced for a while at least.

It was a difficult matter to form any definite conclusions as to the character of service rendered by these municipally owned utilities. Since the war broke out, their electrical loads have been light and therefore they have been able to give excellent service as regards voltage control, lack of interruption, etc. It was therefore necessary to make inquiries over a period of years and these developed some interesting facts.

During the period of rapid growth in these cities the councils of the time were so engrossed in street extension, pavements, water projects, etc., that they could spare but little attention or funds for electrical plant needs. In consequence the plant was allowed to become overloaded from lack of sufficient equipment to properly handle natural increase of load. A series of interruptions in service would forcibly call the attention of the public to the critical conditions existing in the plant. Then a demand would be made for instant action and machinery would be purchased in many cases solely on the speed of delivery without particular attention being given to the ultimate station plans. This phase of municipal operation could be corrected by a utilities commission, which would have authority to regulate service before extreme conditions existed.

The administration of these utilities as has already been pointed out, is in the hands of either a commissioner, a superintendent or an electrical engineer and when these are free from interference on the part of the council, the utility is administered well and economically.

In a recent discussion of municipal plant operation in Oklahoma, Prof. Bozell makes the following statement:

> In practically every case where a cash surplus of any size was revealed, as well as in every case in which efficient operation and an intelligible accounting system were found, there proved to be someone in the munici-

pality who was devoting a large part of his time to the handling of the plant without any charge to the municipality.

A review of the utilities of Western Canada does not reveal any such condition to exist in these cities, for with the exception of Kamloops, the municipalities are large enough to employ competent superintendents.

In Manitoba, a public service commission has authority over public utilities. A similar commission has been appointed in Alberta since this investigation was made. But, at present there is no executive board in either British Columbia or Saskatchewan with such authority. Hence the municipal enterprises of these provinces are at the tender mercies of the common councils of the cities and towns. Such bodies have frequently in the past committed their municipalities to ill-advised extensions. It would seem advisable to have an executive board in each province organized along the line of the railroad commission of Wisconsin, who would have the necessary executive authority and with duties about as follows:

(a) To pass on all new extensions and expenditures of public utilities and to see that funds are spent on the improvements for which they are set aside.

(b) To receive and approve financial reports of the utilities and to adjust sinking funds and depreciation charges.

(c) To adjust equitable rates without discrimination and to scrutinize the disposal of surplus.

(d) To establish standards of service that the utilities can meet and that customers can reasonably demand. Owing to changes in the state of the art, these standards require frequent revision. Such changes usually result in improvement of service frequently at a lower cost.

(e) To collect engineering data and to provide engineering assistance to municipalities undertaking new enterprises. The commission should also be empowered to pass on the plans of all new projects.

(f) To advise with municipal authorities regarding the floating of debentures and to assist in a material way in marketing these. In many cases those in charge of the financial affairs of small towns have never had experience in these matters and competent assistance and advice would be most welcome.

Such a board should consist of only highly trained men experienced in this work and should preferably have three members, an engineer, an accountant and an economist. On no account should a man with a political record be allowed a place on such a board. In fact, it might be even advisable to appoint men from outside the provinces who would thus be free from local

prejudices and political affiliations. The board could act in an advisory capacity for municipalities on all matters dealing with utilities. Such control would have prevented many of the mistakes made in the needless extension of utilities and would have insisted on sound financial conditions in all utilities.

The establishment of such a commission would not necessarily curtail the control of any municipality over its own utilities. The local councils would still have the power to regulate rates, etc., subject only to review by the utilities board on appeal by one of the local consumers.

A further function of such a board would be to exercise executive control over the surburban and interurban activities of the utilities. Difficulties frequently arise in regard to the control, the rates and the service outside the municipal boundaries and beyond the control of of the city's authorities. These could be equitably adjusted by the commission.

Another useful activity of such a commission would be the standardization of the accounting systems of the various utilities. The difficulties met with in preparing the summary given in Table IV and the difference of opinion as to its accuracy as regards distribution of expense, make evident the need of such standardization if comparisons are to be made between the costs of different cities. Several of the public utility commissions in the United States have standardized utility accounting in a satisfactory manner.

Such mistakes as have been made by the executives of these municipal undertakings have not been intentional nor due to carelessness. Generally these errors were in connection with matters with which the official had no previous experience and at the moment lacked competent counsel. The inauguration of a friendly spirit of cooperation between utility executives and the proposed commission would do much to materially improve matters in the future, for the commission could be called on for consultation whenever new difficulties were encountered.

Conclusions

In the preceding discussion, emphasis has been placed on certain principles that should be applied to the organization of municipally owned utilities. These may be briefly summarized as follows:

(1) The utility should be entirely self-supporting, and consumers should be charged such rates that the returns will meet all the usual expenses of

the business but will not provide balances to be used in extensions or improvements or to offset losses in other departments.

(2) The utility should be under the direction of a single commissioner or superintendent holding office on good behavior and who should be given a free hand to develop the utility without political or civic-council interference.

(3) The utility should bear its portion of the cost of general municipal government through assessment and taxation. The latter should be paid from revenue and the rates to consumers should be adjusted to provide these funds.

(4) The utility should be financed by means of serial bonds instead of long term debentures and all such issues should equal only the life of the improvement they are intended to cover.

(5) Obsolete machinery should be written off the books at once, either by using surplus funds or by increasing rates. Depreciation or replacement funds should be set aside from revenue to provide for the renewal of the plant when worn out.

(6) An emergency reserve fund of moderate amount should be accumulated out of surplus to meet extraordinary contingencies.

(7) All improvements and extensions should be financed by additional bond issues and not from surplus funds.

(8) The net surplus of the utility should be distributed in the form of proportional rebates to consumers.

(9) A public utility commission should supervise the finance, accounting, rates and administration of the municipal as well as privately owned utilities of each province.

The preceding discussion of facts and conditions connected with the organization, financing, operation, rates and service of the electric light and power utilities of these cities of Western Canada, leads one to the following conclusions in regard to the general criticisms of municipally owned public utilities stated in the opening paragraphs of this paper.

(1) The rapid growth of these cities has forced the executives of their utilities to make frequent extensions to their plants which on the whole are therefore well equipped with modern and efficient machinery and provide satisfactory service.

(2) Rates for lighting and power are as low and in many cases lower than those in force in cities of similar size in the United States and are reasonable charges for the service rendered.

(3) Accounting as a rule is now carefully done and the utility's finances are isolated from other accounts. Some of the methods of financing as regards debentures, sinking fund, depreciation and surplus are open to some criticism as shown in the preceding discussion.

(4) Most of these utilities have been fortunate in having good organization with competent executives.

(5) There may be isolated cases where politics has influenced the management of the utility. But there was nowhere evidence of the

application of the "spoils system" to the municipal plants and in the majority of cases, the utility has been tolerably free from political interference.

It must not be assumed that this paper is an endorsement of public ownership. An effort has simply been made to present the facts that came to hand during visits to the various cities, without bias either for or against municipal ownership. If this article seems to favor municipal ownership or control, it is only because the facts as they were found, pointed in that direction. Such criticism and suggestions as have been made in this discussion are offered in a friendly spirit and in the hope that they may prove of benefit to these Western cities. In conclusion, the writer wishes to acknowledge the great assistance rendered him by the officials of these cities in the collection of data and in the inspection of plants and systems.

DISCUSSION ON "THE MUNICIPALLY-OPERATED ELECTRICAL UTILITIES OF WESTERN CANADA" (CHRISTIE), NEW YORK, FEB. 8, 1916.

Philander Betts: I think of all those who are opposed to municipal ownership, those that know most about it are the engineers and operators, etc., of utilities. Among those who favor municipal ownership and operation, I think we will find only a small number of engineers. The others are economists, publicists, politicians, most of whom are honest, but the list includes demagogues and others whose arguments are based on personal benefit.

In the observation of the operation of utilities in the State of New Jersey during the past five years, and during the past three years more particularly, since the Commission has prescribed classification of accounts and has called for annual reports from municipally-operated utilities, there has been an opportunity to observe the operations of these utilities, and what stands out most markedly is the chaotic way in which they are operated and managed. The condition in Western Canada appears to be quite different, and brings out some things that I think we have all got to take account of.

I think the paper sounds a word of warning, in a way, and I want to point out what that is. In the first place, municipal financing is based on a theory different from the theories on which our ordinarily operated public utilities are financed. The publicly owned utility or project of any kind is financed on the theory that it will suffice for this generation or for the life of the project, and that a scheme of financing must be worked out so that any bonds issued to pay for that project must in some way be taken up by the time that project is worn out, in this way leaving the future generation free to finance its own projects and determine for itself whether it will renew them. This applies to projects other than utilities, and includes roads, school houses and other public matters.

In regard to public utilities which are privately owned, we are working on a theory that these things go on forever, perhaps not as they are at present constructed, but in some form, and our financial schemes are based on the idea that they will go on forever, that they must be maintained and replaced as they become worn out, and that the capitalization needed to construct them continues and is not entirely retired at any time.

This latter method of financing, if all other things were equal, would really mean cheaper rates, if the capitalization is not retired. That is a mathematical problem, capable of demonstration with a little trouble, but not a matter, I think, which is worth while going into now.

In order to know definitely whether municipally-operated utilities are any better than privately-owned utilities we must have proper methods of financing, proper methods of recording the various transactions involved in the construction of the plants

and of recording the transactions involved in the operation of these plants, and the accounting systems must be imposed by some power superior to the municipal authorities. In New Jersey our greatest difficulty has been to place the responsibility.

Last year twelve of the municipalities in New Jersey operating water departments were summoned by the Commission to explain why they had not furnished a full report of the operations for the preceding year. In each case the Mayor or the Clerk of the Council, or some official, tried to throw the responsibility on some one else, and it developed that almost all municipal operations are conducted on what to a business man is an inexcusably chaotic basis. Receipts, revenues from the operation of the municipal utility, are considered and handled like any other municipal revenue. They are taken up, handled and carried along in the same accounts with taxes, with license fees, and with other revenues. The costs of operating a municipal utility, on the other hand, usually come out of the proceeds from taxes.

Without a proper system of accounting no one knows whether the system is operating successfully or not, from a financial standpoint, and to my mind that is clearly improper. There are a few cases that stand out in considerable contrast, in which the utilities are operated as a business proposition, in which the revenues, expenses, and all the accounts are handled through one department in such a way as to show whether the project operates at a gain or a loss.

In making a proper comparison, however, Prof. Christie has called attention to the matter of taxation. To show how important it is that all municipal utilities should pay their taxes just like any other utility, I want to call attention to a condition in one of the counties in New Jersey, consisting of about twelve municipalities. Ten of these municipalities own their own water departments and two of these municipalities are served with water by private companies. In the system of taxation in force in New Jersey a part of the tax money furnished by the municipalities goes to the county to support the operations of the county and, therefore, a tax collected in one municipality is of benefit, in a way, to all of the municipalities within that county. If the water companies in these two out of the twelve municipalities pay their full share of taxes a large portion of that tax is expended for improvements in the other ten municipalities.

That condition is recognized by many of the municipalities in New Jersey, and has led to a system of trading, by which the municipalities have said, or a particular municipality has said, to the water company—"we don't want you to pay taxes and in turn we will not pay for the municipal water service that we get for our City Hall and School Buildings and Fire Houses, and in many cases for the fire hydrants. We will just exchange credit for these things, and we recognize that we as a municipality, and our citizens within our municipality will be better off, we will keep within our municipality the full amount of money that would be paid by that utility in the form of taxes."

Is that a proper state of affairs? I think not, and I think that shows the necessity for every utility to pay its own taxes, whether it is municipally operated or not, provided any utility is to pay taxes, and it appears to be a well established thing that all property is to be taxed as we now understand these things.

There is another feature which is very important in the operation of a municipal utility. In a few cases in this country—Anderson, Indiana, is one—the service of the utility is paid for at regular rates. Every bit of service furnished by the utility, service for the lighting of the school houses, of the police stations, and other municipal buildings should be paid for in accordance with the regular rate. Street lighting service should be paid for, taxes should be levied, actually, for that specific purpose, and credited to the utility, just as they would be if that utility was operated by a private corporation.

A municipally-operated utility ought not to confine itself, if it is to do its proper duty to the public, solely to any matter of street lighting. It ought to be treated like any other utility, considered as a natural monopoly, and not only be allowed to, but required to furnish every class of service needed in that municipality. It ought to do the lighting, other than street lighting, provide all the necessary industrial power, and all current required in the municipality for any ordinary purpose.

Now, let us consider this question: If every utility was treated exactly the same way, financed in a proper way, kept its operating accounts in a way to show the real result, and if there was an equal amount of efficiency displayed in the financing, construction and operation, then would there be an advantage to the municipality that owned its own utility? There might be in this one way—in the regulation of rates we are often confronted with claims for value which have no basis in connection with the investment. The investment itself might be made up or considered as of two parts, actual investment in the physical property and everything that goes with that, and the investment, just as much an element of cost as anything else, that comes from the lack of earnings in the early years, lack of profits, and the unearned depreciation which must not be forgotten.

Instead of setting up a claim for a value as a going concern, which is the value that ought to be taken into account in a case where one purchases a property as a going concern, or where property is sold,—in claiming a value of that kind, I think we get away from the proper basis, and that is the investment;—a just consideration of the investment will take into account not an element known as going concern but an element that may be about the same, mathematically. It may be far in excess of any so-called going concern value or it may be less, and that is "cost of establishing the business." That includes this lack of earnings in the early years, lack of profits as time goes on, and this unearned depreciation due to the gradual and growing obsolescence of plants and the necessity for replacing them before a reserve has been accumulated to provide for that purpose.

If the claims set up by the company extends that far and no further, then there can be no advantage whatever that can accrue from municipal ownership, provided that in connection with ownership by municipalities the financing and accounting and all operating conditions shall be carried on in exactly the same way that must be done by any efficient business organization carrying on the same class of work.

Henry G. Stott: The fundamental point, it seems to me is this.—Is there any difference between a municipally owned plant and a privately owned plant? Either a municipality or a private individual can buy efficient apparatus, one can construct as efficient a plant as the other. The next question is—What are the objects to be gained under the two classes? In one case, theoretically, the municipal ownership plant is constructed to give service at cost. In the other case, of the privately owned plant, or incorporated plant, admittedly the object is not only to give service, but to make a profit. Under these two plans it would look as if the municipally owned plant ought to give the cheapest service, other things being equal, but actually what do we find? We find this, that in the municipally owned plant as a rule—I am talking about conditions in this country—the plant becomes the prey of politicians.

In one case there is a basis of trading political preferment without any desire to earn dividends. In the other case there is an actual and avowed desire for gain. There is no secret about it. The privately owned corporation exists to make money for its stockholders, and therefore must be operated efficiently. These are the two fundamental differences.

If we can get away in the municipally owned plant from the idea that every alderman or councilman or politician has a right to send men around for this, that and the other job in connection with the municipally owned plant, and if there are no jobs open for them, the jobs must be made, with the resulting demoralization of the staff, then the municipally owned plant will be equally efficient and equally well operated as the private plant—there is no doubt about that—but we have no symptoms of that change in method at the present time.

The biggest problem in the electrical industry today in connection with the business of supplying power, is the question of obsolescence. In the case of the average plant today the greater part of the machinery becomes obsolete in from ten to fifteen years; very little of it lasts fifteen years, the average is about twelve years. I know of one case where a piece of apparatus which cost a quarter of a million dollars twelve years ago was scrapped recently and sold for $8000. We should establish an obsolescence fund. It is a proper charge against the cost of making power, because we know as certainly as it is possible to know by the history of the past that in the future there will be further developments, so that during the course of every decade or a little more, we must completely revolutionize our plant. This is a difficult thing to have recognized in any

municipality today, the fact that a charge for obsolescence is a proper one to make.

If we could, as Mr. Christie suggests, have one man put fully in charge of a plant and make him absolutely responsible for the operation and for the financing of it, and have every one connected with the plant follow his instructions without outside interference, then I see no reason why the municipally operated plant should not be operated equally advantageously with the ordinary privately owned plant. But they cannot be upon any equality, until we get rid of the idea in this country that the municipally operated plant is the means of passing around favors for the politicians, and until we put it on the basis of actually earning a revenue for the stockholders who are the tax payers of that city.

R. P. Bolton: Mr. Christie has almost wholly disregarded an essential element which is rarely offered and generally almost impossible to secure in regard to municipal undertakings. This is not only the rate or cost, but the extent of the contributions made to the income of municipal utilities by other branches of the municipality. The paper contains but one slight reference to this subject.

My investigations in Winnipeg and a number of cities in Ontario, have convinced me that municipal officials generally guarantee either an excessive use of electricity or charge high rates for energy supplied for municipal purposes. In fact I have found instances where the amount guaranteed has deliberately been made sufficient to secure the appearance of a surplus upon annual operation.

I can offer a particularly definite illustration of this in the operation of the municipal hydroelectric system in the City of Toronto, from the report of which for the year 1914, I take the following figures:

Out of a total income of $1,501,291, no less than $562,353 was derived from the payments made for the lighting of streets, of public buildings, and for power used in municipal water supply, pumping, etc. The total cost of the electric energy supplied, both for municipal and for all commercial purposes was $324,236 while the charges paid for street lighting by the municipality to the electric system amount to $364,214. For municipal power purposes, the sum of $157,700 was paid. I learned that the cost of electrical operation of the pumping service was in excess of that for steam operation, and that the chief engineer of the water department resigned his position several years ago following the disregard of his protest against the change of system made necessary by the attempt to supply electric service to the municipal pumping system.

So far as street lighting is concerned, the cost for 1914 may be compared with the cost prior to the establishment of the municipal system, when the city was lighted by the Toronto Electric Company at a total cost of $135,000. Thus, in about five years of operation, the cost of street lighting has been nearly trebled.

The result of these excessive contributions by the municipality was, for the year 1914, to bring about a surplus amounting to about $4\frac{1}{2}$ per cent of the total income which, as is evident from the foregoing figures, is not real but merely apparent.

The total energy used for the year 1914 of this municipal system was as follows:

For residential and commercial lighting, kw-hr. . . 13,752,500
For commercial power, kw-hr. 20,724,800
For municipal purposes, light and power, kw-hr. . . 50,115,000

It may be conceded at once that the large quantity of energy absorbed for municipal purposes warrants a low rate per unit, but it is the total contribution which brings about the effect upon the municipal accounting.

In making investigations in Winnipeg, I found that very similar conditions obtained there. I was informed at the time of my last visit that the city pumping department was being charged a higher rate for energy than was a commercial undertaking in the immediate vicinity, although the city pumping was an off-peak load and the commercial operation a twenty-four hour load.

The situation in Winnipeg has not been quite fairly reported to Mr. Christie, judging by his description of it. The private corporation to which he refers had been in operation since the year 1892, and, during the greater part of its existence no dividend had been earned upon the capital invested. At the time of the commencement of the agitation for a municipal electric system upwards of $4,000,000 had been invested by this company, upon which only 5 per cent was earned, while the arrears of unearned dividend at that time amounted to nearly $300,000. The agitation was not directed by any necessity for a supply of very cheap power, since power was at that time available for industries at rates as low as they are today. The company had also voluntarily reduced its rates for domestic service and the maximum charge for the minimum service was the ten-cent rate.

In point of fact, the agitation for a flat three-cent rate for domestic service in which the city has become involved was started by cetain ill-informed persons for political purposes. This unfortunate local agitation has resulted in a total investment of nearly $7,500,000 and the bonded indebtedness of the city has been increased 33 per cent by the process. As in the case of other cities described by Mr. Christie, lying further west, the result has been disastrous to the credit of the communities, and in my judgment, the present unfortunate situation in western Canada is largely attributable to this unnecessary class of investment. The same remark applies in a degree, to cities in Ontario.

The extravagant investments of these cities and particularly of Winnipeg, are due to an ill-informed faith in hydroelectric generation of energy, involving expense far in excess of that of first class steam power plants, and presenting very often great

difficulties in the way of any future radical change or enlargement. This point is well illustrated by conditions in Winnipeg, the cost of its plant per kilowatt of installed capacity being \$132. A first class steam plant might have been built at \$50 per kilowatt of capacity. The fixed charges on the difference of \$82 upon the output recorded for the year 1914, amount to 0.37 of a cent per kw-hr. which is equivalent to the cost of coal at the rate of 1.8 pounds per kw-hr. and at the price of \$4.00 per short ton. The excess investment amounting to \$2,500,000 has, therefore, little or no commercial value.

Moreover the municipal plant in Winnipeg as in other places, is lacking in stability as a result of the liability to failure of all hydroelectric and transmission systems, and is in this respect at a disadvantage when compared with the system established by the private company which has a large steam power plant in the city. From these facts a peculiar situation has arisen. Sundry consumers upon the municipal system are paying for breakdown service on the private system as a reserve, being thus put to double expense.

The State of Manitoba has established a public service commission system, one of the problems of which, as described to me by the Commissioner, was how to deal with the unfair competition established by municipally operated systems like those in Winnipeg. The various municipal systems in the province of Ontario are under the control of the Hydroelectric Power Commission of that province by which a uniform system of accounting has been established recently. In this accounting system depreciation must be provided for. No provision, however, is made for the bringing out of the extent of the contributions of the municipality toward the support of its electrical utility. I have investigated instances in which, in order to make up a prior deficiency, the amount of street lighting in a small town has been doubled in a year.

In view of this feature of Canadian municipal operations, it would seem necessary that all the facts should be known before decision as to their financial failure or success is made. Information in the paper is, as I have said, meagre, but enough is stated to indicate that the process I have described is evidently being followed. Thus, for railway services, prices are apparently charged which vary all the way from 1½ to 2 cents per kw-hr. Arc lamps are charged as high as \$65 and \$70 per annum. In Calgary, the street lighting is charged at the rate of \$24 per 100-watt equivalent. Doubtless further investigation by Mr. Christie would bring out other remarkable illustrations of the methods by which this process is pursued.

My own attitude toward municipally operated utilities is dictated by a desire for fair treatment and full consideration of the right of communities to decide whether they will pledge their own credit to effect certain results or allow other persons to do it for them, at a reasonable price. But I regard it as the first

duty of the engineer to avoid deceiving himself and deceiving others. I have never been able to find that the municipally operated utilities in Canada were free from methods open to criticism as being unequal in effect and unfair in method. Until we can be informed fully upon every important phase of the subject, judgment as to the relative efficiency and financial success of the Western Canadian municipal utilities should be suspended.

Edward J. Cheney: Mr. Christie gives us a good deal of information on what can be done, but the real question is—what *will* be done—in the situation in which we are interested. When our city governments can conduct present operations in an efficient and economical manner, it will be time to say that we can take up the municipal ownership and operation of public utilities on a satisfactory basis. For whatever reason it may be, municipally owned plants in this country do not show as successful operation as Mr. Christie shows for the Canadian ones. There are some notable exceptions, but I think invariably they are due to the fact that some broad minded, public spirited citizens, without compensation, have taken charge and kept the operation out of the hands of selfish interests.

The country which Mr. Christie has studied is new. The very rapid growth of the territory is in itself favorable for successful operation. The citizens appear to be non-political and interested in general business affairs. That atmosphere is not conducive to the development of politicians or their education in the use, for selfish purposes, of publicly owned utilities.

I do not wish to appear pessimistic, but there is some indication in the paper that those conditions may be changing and it is possible that those cities may ultimately reach that unhappy stage of development, with which we are fairly familiar in this country, in which the possibilities of exploiting the public utilities are well understood and fully taken advantage of.

It is suggested that state or provincial regulation could be used to smooth out and correct the irregularities of the municipally owned plant. Now, in this state we have state regulation which theoretically controls such plants, but the trouble is to find the man or the set of men or the organization that you can control. How do you get hold of anybody you can do anything with? I know of one instance in which the electric distribution system in a certain city was in a deplorable condition. It not only rendered good service impossible, but was an actual menace to life. The matter was taken up with the men who had charge of the plant, and these men said—"Well, we would have to go to the Board of Aldermen, and if the Board of Aldermen submitted to the citizens a bond issue, the citizens would not vote for it. We have no money and what can we do about it?" What, as a matter of fact, can be done in such a case? You cannot make men, who have no money, do anything which requires the expenditure of money, and you cannot make an order directing the citizens of a city how to vote.

Clayton H. Sharp: Is it not due to the municipal trading in these cities of western Canada that the ratio of municipal bonded indebtedness to assessed valuation of property is much higher than is allowable, for instance, in any city in the State of New York? It might be interesting to have some statistics as to the ratio of bonded indebtedness to assessed valuation.

Is it not true that municipal trading is somewhat responsible for the fact that the debentures of these cities have to be sold on the market at prices at which they will pay the investor in every case considerably more than five per cent, and often as high as six per cent?

Arthur Reid: There are one or two points in the Lethbridge plant information that are not quite correct.

Prof. Christie gives the cost of plant in Table IV as $456,370.78 and the rated kw. as 2300. This value is evidently the items "land, bldg., and machinery and tools" in the auditors statement.

This is not altogether correct because $2,000.00 of the tools account would be charged to the distribution cost. Although the auditor's statement does not show an itemized statement of the amount under "land, bldg., and machinery," this amount includes the following which should not be charged to the present electric plant.

Cost of pumping plant and alterations to power house building, to accommodate pumping plant..	$53,138.00
Cost of old plant destroyed by fire..................	48,200.00
	$101,338.00

Actual cost of new plant $456,370.78 − $2,000.00 − $101,338.00 = $353,032.78 ÷ 2,438 kw. = $144.80 per kw.

He has given the rated kw. of plant as 2300 instead of 2438, if you add the capacities as given on the plates on the machines viz: 350, 588 and 1500, you will get the above figure. Lethbridge as well as Saskatoon, had a society started by myself for mutual improvement along technical lines for the departmental employees.

In addition to the reason given by Prof. Christie, for the utility being taxed on the same basis as other industries, we have always put the following reason first—The money borrowed to create the utility is borrowed on the credit of the whole city and therefore the municipality is entitled to some return for this credit.

Regarding the disposal of surplus, since the city of Lethbridge purchased the electric plant, it has always been the policy to cut the rates for electricity to produce a revenue as near the operation costs as possible and what little surplus remains is transferred to general revenue.

The reason for the above is, because the electric light and power consumers are nearly all rate payers, if not directly, then indirectly through landlords, etc.; then, if the rates are high enough to produce a large surplus and this surplus is paid into

general revenue and goes to reduce taxation, the electric light and power consumers are being overcharged to help reduce the taxes on all property including that held by parties living in other parts of the world who do not contribute one cent of the electric revenue. Therefore, it appears to me, that the only fair way is for the utility to pay the same rate of taxes as any other industry and keep the electric rates as low as will produce a slight balance on the right side of the books. This is what the city of Lethbridge has endeavored to do. Of course, in following out the above, you lay yourself open to the danger of a falling off in the receipts and are then likely to face a deficit at the end of the year, but I think this should be taken care of by putting surplus that may accrue, into a contingency fund to take care of such an event.

A. G. Christie: Mr. Betts has brought out very clearly some points in financing that deserve attention. He justly insists that the utility itself should bear all costs connected with its financing and operation. Too often the equipment does not last as long as the life of the debentures.

Mr. Scott has emphasized in his discussion one of the most important essentials for success in municipal ownership, viz— one-man control. This, and the spirit of cooperation between citizens and the utilities seem to me to be the real basis for the results shown in the West.

I have had considerable difficulty in impressing on municipal officials the necessity of figuring ample obsolescence allowances, and Mr. Stott's statements in this connection will materially assist in emphasizing my point in regard to the short life of present-day machinery.

Mr. Bolton's contribution to the discussion is very timely for by introducing the question of municipal revenue to the utility, he calls our attention to a factor that in times past has been one of the greatest shortcomings of public ownership. However, genuine attempts are being made in western cities to overcome these defects by charging for all service on the meter basis. But, as is shown in the paper, several still maintain fixed rates per lamp, and are thus still open to criticism.

In regard to Mr. Bolton's figures from Toronto, I am not intimately familiar with the situation there. However, these hardly seem fair, for he considers only lump sum figures and does not present the cost per unit or the increase in the effectiveness of the lighting system. From 20 years acquaintance with Toronto, I am able to say that it has never been better lighted than at present, and this of course, takes additional power. Furthermore, Mr. Bolton apparently discounts also the rapid growth in population and extent of Toronto from 1909 to 1914.

When one discusses Winnipeg, its situation must be clearly kept in mind. The long haul from the Alberta coal fields made the cost of steam power prohibitive. Hence the people naturally turned to water power which is available in great quantity in

the country to the northeast of the city. Whether Winnipeg was warranted in expending so much on its hydroelectric system is a difficult question to discuss, yet the fact remains that the electrical utility is supplying probably the cheapest electrical power in America and is earning a surplus at the same time.

In regard to Mr. Sharp's question about bonded indebtedness, I must admit that I am not familiar with New York state figures, and I do not believe that I have the necessary figures from the cities of Western Canada to make satisfactory comparisons. I believe, however, that the ratio of bonded indebtedness to assessment will be found higher in the West than in New York.

It would puzzle one to get a fair basis for comparison in regard to assessment. Some cities are under single tax. Others have cut assessments since war broke out, while others have very inflated land values on all real estate.

The high rate of interest on Canadian municipal bonds was largely due before the war to considerable doubt among British financiers of the ability of these municipalities to pay for these debentures. They failed to realize the rapid growth of these cities. On the other hand, some cities like Saskatoon started out on too ambitious a scale.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

CREST VOLTMETERS

BY C. H. SHARP AND E. D. DOYLE

ABSTRACT OF PAPER

The paper shows how a voltmeter which will read directly the maximum or crest values obtained in high-voltage testing may be constituted by a combination of an electrostatic voltmeter and an electric valve. Diagrams of connection are shown and results of test given to indicate the validity of the method.

STRESSES in dielectrics subjected to alternating voltages are proportional to the maximum rather than the mean effective value of those voltages. The ordinary voltmeter which reads r.m.s. values is nevertheless the instrument ordinarily used in high-voltage testing, and the assumptions are made that the crest factor, that is, the ratio of the maximum to the r.m.s. value of the wave, is that corresponding to a sine wave, 1.41, and further, that it does not vary therefrom. These assumptions are made with the full knowledge that in the general case they cannot correspond strictly to the facts, but the lack of a suitable instrument for reading crest voltages has made it almost imperative to adopt this course. Quite apart from the ordinary deviations of the wave form of alternators from the sine curve, the variations in wave form with the load on the transformer which are encountered in high-voltage testing are often exceedingly serious and sufficient to introduce errors which are very important indeed; especially since they may be unknown and unsuspected. This renders highly desirable a suitable instrument for reading the crest values, and hence giving results independent of these variations.

As illustrations of some of the variations which occur in actual practise, Figs. 1, 2 and 3, all taken from different testing installations in practical use, are given, which with their captions are self-explanatory. Fig. 3 is particularly striking as showing a change in crest factor of 25 per cent with quite a small change in the load. It is evident that a condition such as indicated here was an intolerable one where, as was the case,

a product of great monetary value was being tested on the assumption that the wave was of sine form and invariable.

An instrument is available, and is recognized by the Standardization Rules of the A. I. E. E., whereby these maximum values may actually be measured. This is the spark gap, fitted either with needles or with spheres. Without going into detailed consideration of the shortcomings of the spark gap, it may be noted that it is deficient in that it can be set for one voltage only and gives no indications, except by breakdown, of the voltage to which it is subjected. It has been very aptly

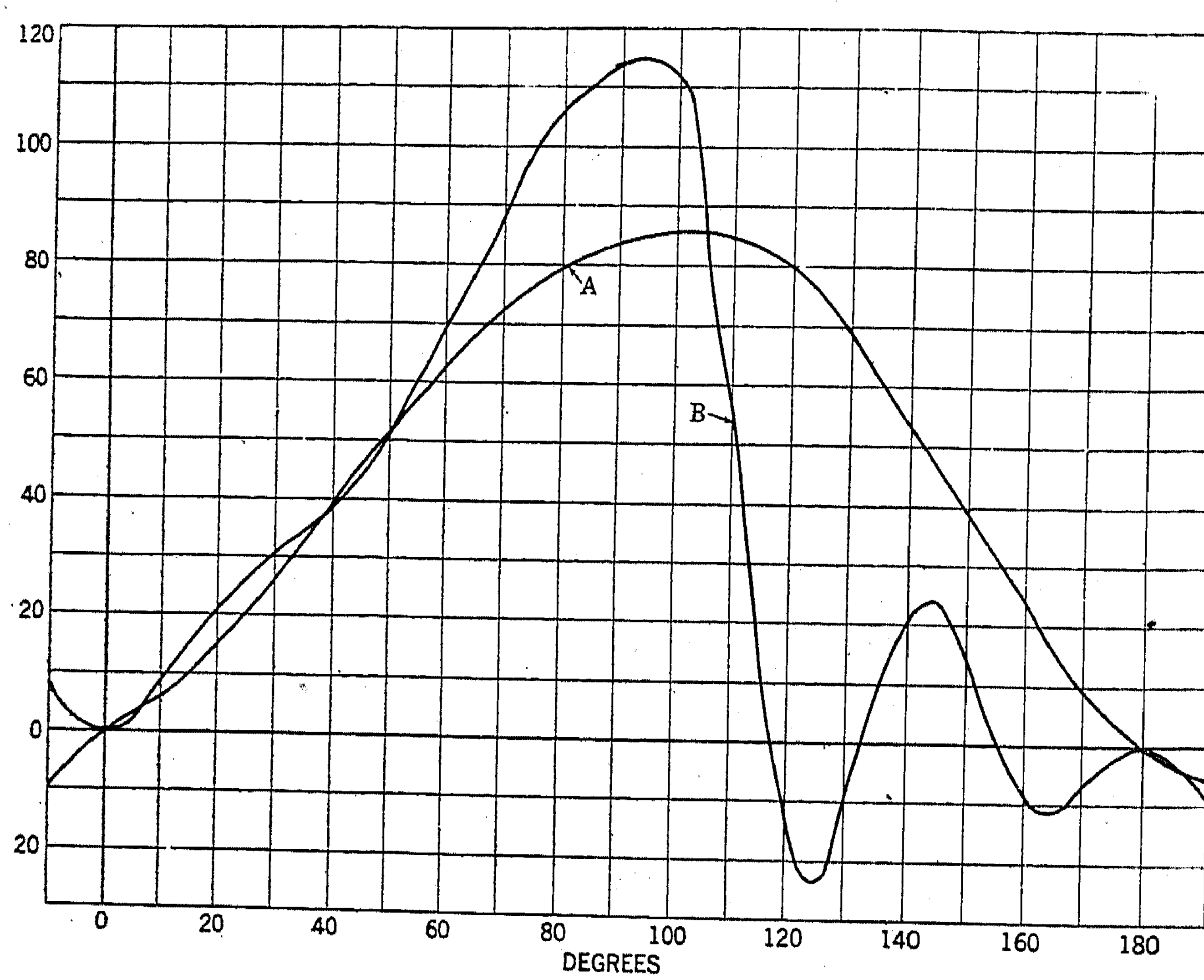


Fig. 1—Wave Form Distortions in a Testing Transformer Introduced by Improper Voltage Control Apparatus

A—Wave form of supply circuit.
B—Wave form of secondary of controller under load.

said that measuring voltages with a spark gap is like measuring current with a fuse. A spark gap can be used with accuracy only where it is placed at a sufficient distance from all extraneous bodies which might influence the character of the electrostatic field in the gap. The precautions required are outlined in the Standardization Rules. The breakdown value of the spark gap is also affected by the pressure and the relative humidity of the atmosphere. The variations due to humidity have not been standardized. The Standardization Rules say "If proper precautions are observed, the spark gap can be used to advantage in checking the calibration of voltmeters when

set up for the purpose of high-voltage tests of the insulation of machinery."

1. Sharp and Farmer[1] have described a crest voltmeter in which an instantaneous contact apparatus driven by a syn-

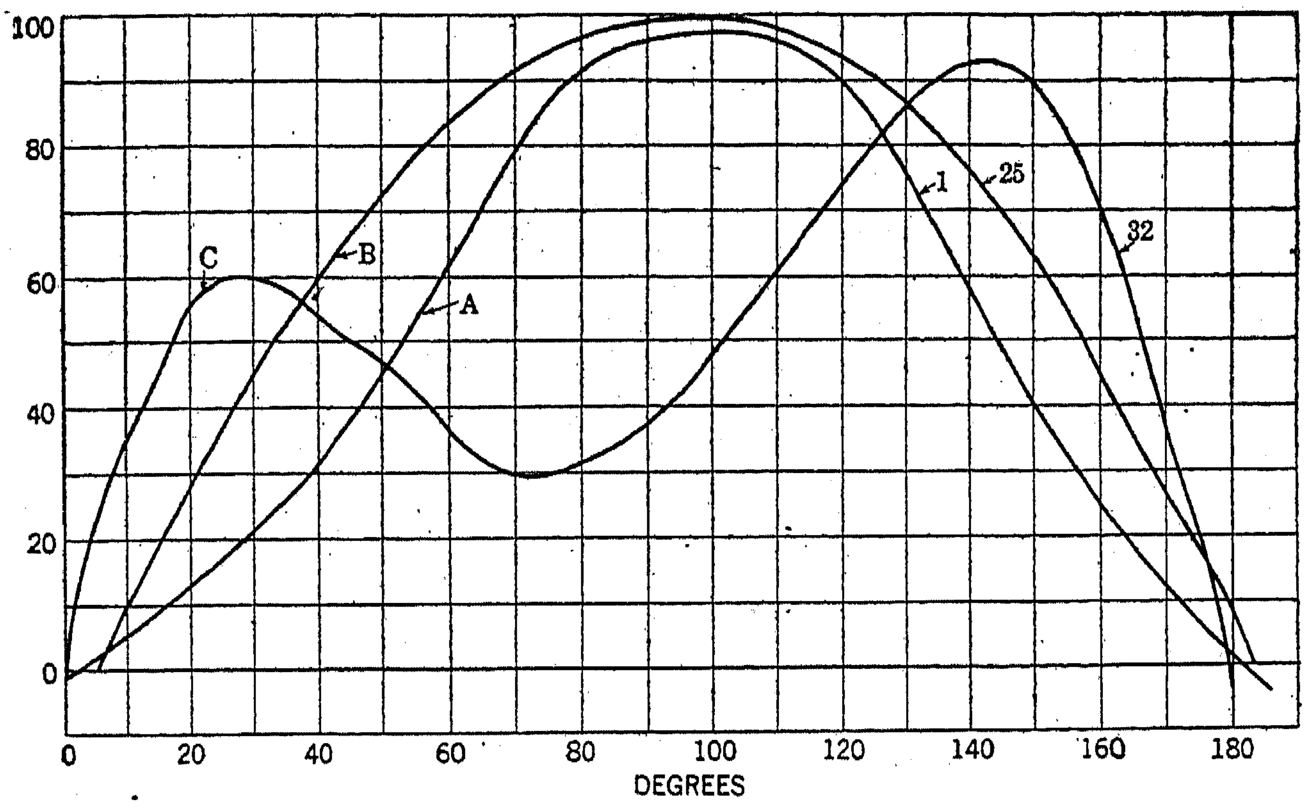


FIG. 2—WAVE FORM OF TESTING TRANSFORMER VOLTAGE

A—No load; crest factor = 1.11 × 1.41
B—Light load; crest factor = 0.98 × 1.41
C—Heavy load; crest factor = 1.15 × 1.41

chronous motor allows an electrostatic voltmeter to be put momentarily in contact with the high-voltage circuit at the crest of the wave. The voltmeter is thus charged up to the crest voltage and indicates this value. For steadying purposes a condenser is placed in parallel with the voltmeter. This

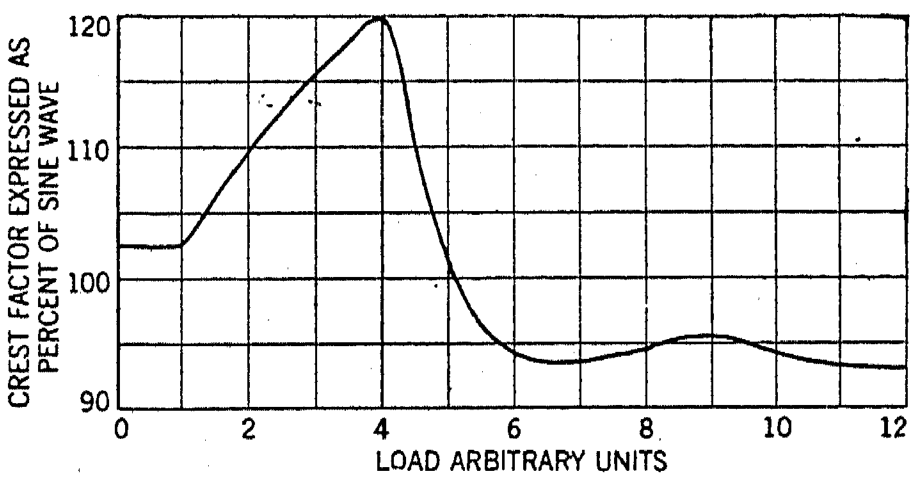


FIG. 3—VARIATION OF CREST FACTOR OF TESTING TRANSFORMER WITH LOAD CREST FACTOR EXPRESSED AS PERCENTAGE OF SINE WAVE VALUE

apparatus can be used on a condenser multiplier from the high-tension circuit or from voltmeter windings on the high-tension transformer, or from a calibrated step-down transformer. It suffers under disadvantages as follows:

1. TRANSACTIONS A. I. E. E., 1912, Vol. XXXI, part II, page 1617.

(*a*) A synchronous motor is required which must be started before measurements can be made, and which will not hunt.

(*b*) The maximum point of the wave must be found by shifting the contact device.

Inasmuch as the angular position of the maximum of the wave will vary as the wave form changes, it is necessary to follow up these shifts of the maximum point with changes in load. This is a troublesome thing to do, and unless it is carefully done, the indications of the instrument will be erroneous. This device has, however, the advantage that the crest voltmeter can be calibrated directly against an r.m.s. voltmeter in the primary circuit, provided the ratio of transformation of the transformer is known. This may be done as follows: With a transformer with a load at which its ratio of transformation is known and with a constant primary voltage of known value, the wave form of the secondary is traced, using the instantaneous contact maker and the electrostatic voltmeter in connection with its multiplier. In this use of the instrument, the method is that given years ago by Ryan. From this trace of the wave form, the r.m.s. value of the secondary voltage as given by the electrostatic voltmeter plus its multiplier is computed. By comparing the true r.m.s. value as given by the primary voltmeter and ratio of transformation with the indications of the electrostatic instrument and multiplier, the multiplying factor is obtained. This is the multiplying factor which must be applied to the crest reading.

2. Chubb and Fortescue[2] have given a method of reading crest voltage, which consists in putting a large air condenser on the high-voltage circuit and measuring the charging current of that condenser by means of a galvanometer which is short-circuited during each alternate half-cycle. Knowing the capacity of the condenser and the frequency of alternations, the measured charging current becomes a measure of the crest voltages.

3. Whitehead[3] has given a method similar to the above in which mercury arc rectifiers are used in series with condensers and some form of ammeter. The connection of the rectifiers is such that the ammeter is short-circuited during one-half cycle. This method obviates the synchronous motor.

2. TRANSACTIONS A. I. E. E., 1913, Vol. XXXII, part I, page 739.
3. A. I. E. E., 1914, TRANS., Vol. XXXIII, part I, p. 951.

4. Lloyd, in 1912, in discussion of the paper of Sharp and Farmer, suggested that the oscillograph might be used as a peak voltmeter. The development of the oscillograph for this purpose has been described by Middleton and Dawes.[4] In this method the length of the band of light drawn out by the oscillograph element measures the crest voltage.

The purpose of the present paper is to describe connections whereby crest voltages can be read on an indicating instrument by a relatively simple apparatus. This method takes advantage of the properties of an electric valve in allowing current to pass in one direction and in stopping it in the other direction. If such a valve is placed in series with an electrostatic voltmeter, it is evident that the voltmeter must become charged to the maximum value of the waves and must retain that charge for a period of time depending upon the insulation of the voltmeter and the valve. The indications of the instrument will be independent of the frequency of the current and of the shape of the wave, except as to its crest value. While the mercury arc rectifier has manifest possibilities as a valve, the pure ionic discharge tube of Langmuir, to which the name "kenotron" has been given, is evidently the most available form of apparatus. Langmuir has shown that in these tubes of practically perfect vacuum, the discharge is absolutely unidirectional. The apparatus is of the simplest possible character and, with proper use, entirely free from any promise of quick deterioration. The only complication is that the cathode must be heated by current, but this is provided for in a very simple manner.

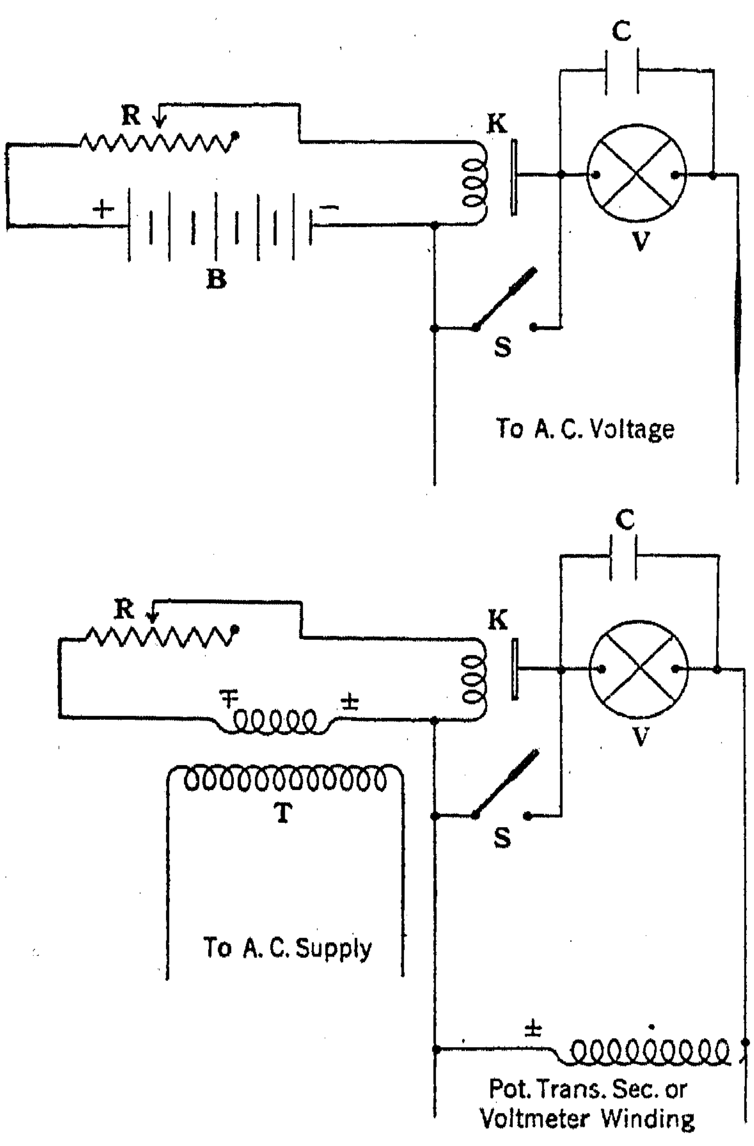


FIG. 4—DIAGRAM OF CONNECTIONS USED IN MEASURING CREST VOLTAGE

V–voltmeter; *C*–condenser; *K*–electric valve; *B*, *T*–heating battery and transformer; *S*–switch short-circuiting valve.

The electrical connections which have been used for this purpose are shown in Fig. 4. The upper half of the figure shows the filament of the kenotron excited by means of a battery of

4. A. I. E. E., 1914, TRANS., Vol. XXXIII, part II, p. 1185.

a few cells. The lower connection shows it excited by alternating current taken from the same source as supplies the testing transformers and stepped down to the voltage of the filament. The second connection is evidently the preferable one, but cannot be used where the high-tension transformer is supplied from an individual alternator with field control of the voltage supplied to the high-tension transformer.

In the experiments here described, the voltmeter used was a pivoted one, directly indicating on a scale of volts and having

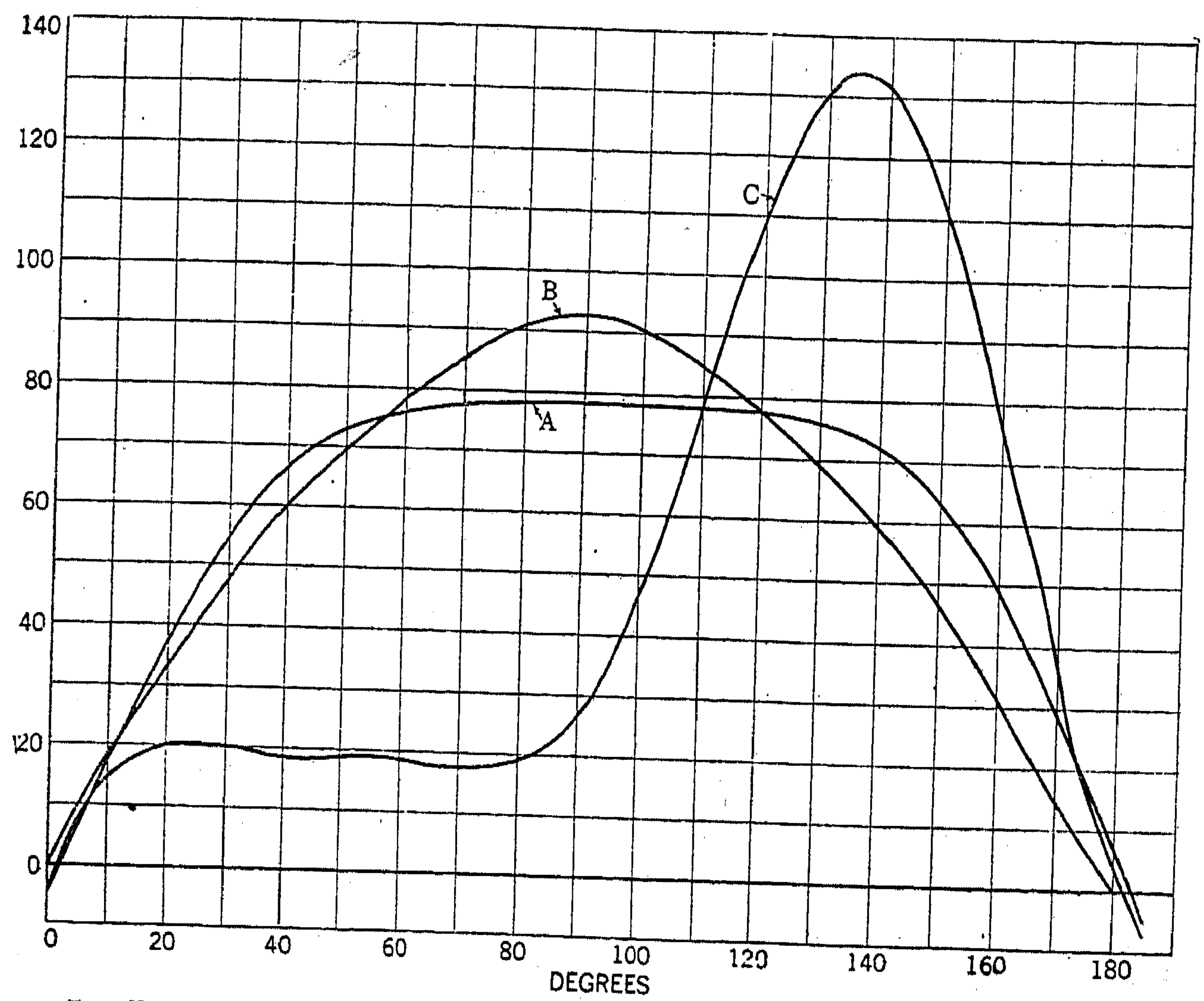


FIG. 5—BUILT-UP WAVES USED IN TESTING CREST VOLTMETER

Crest Factor by

Wave calculation from wave form		Wave meter and dynamometer voltmeter	Crest voltmeter
A	1.218	1.213	1.218
B	1.431	1.435	1.435
C	2.040	2.020	2.090

a capacitance of approximately 1.6×10^{-4} microfarad. In parallel with this is placed a capacitance of 0.02 microfarad or more. With a smaller capacitance in parallel, the leakage of the apparatus was sufficiently great so that the indications were no longer true indications of the crest value. In other words, a sufficient reservoir of charge must be used so that the leakage is a negligible factor. With this arrangement the charge is built up to the maximum value, if not in the first half-cycle then at least in the succeeding half-cycles. This

feature is important in the use of the instrument with a condenser or high-resistance multiplier, inasmuch as it enables the valve with its voltmeter to be put in parallel with a section of a high capacitance or high resistance carrying the high-voltage current, and the result obtained is independent of the actual value of capacitance or resistance used in the multiplier, depending only upon the ratio of the impedance of the portion of the multiplier about which the voltmeter is looped, to the total impedance. The capacitance of the voltmeter itself is eliminated because of the fact that it is retained in the state

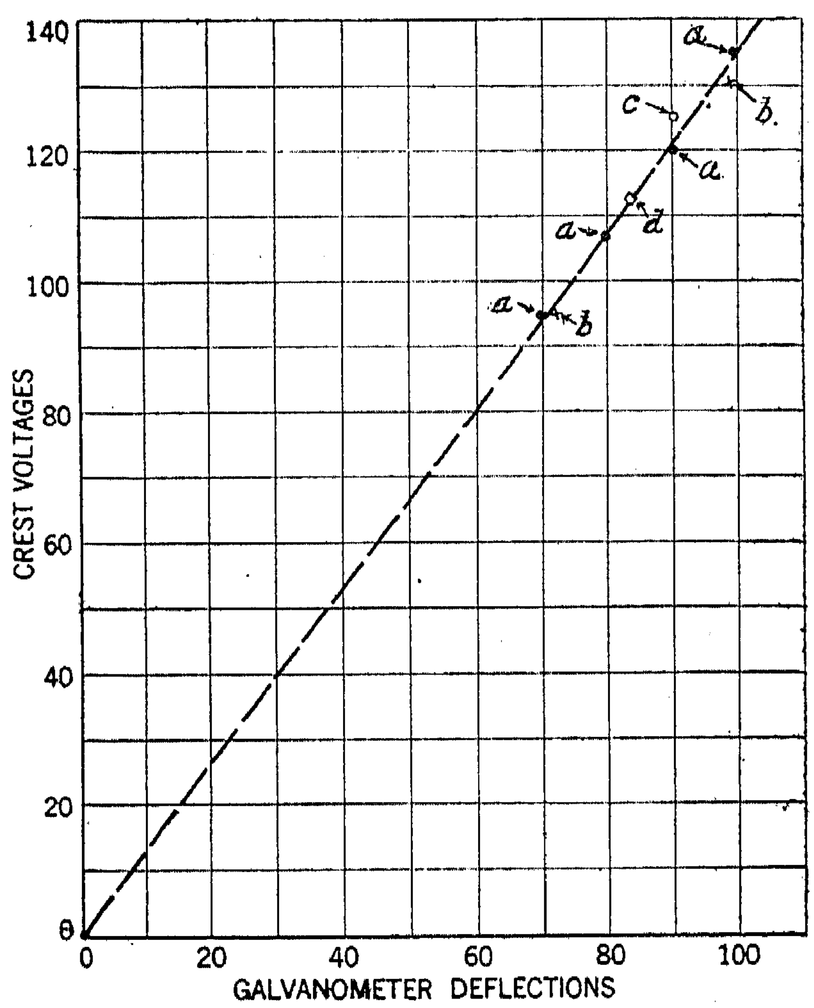


FIG. 6—SHOWS THE PROPORTIONALITY OF GALVANOMETER DEFLECTIONS TO CREST VOLTAGES

Points a	— 60-cycle	sine wave;	crest factor	= 1.41
" b	— 60 "	flat wave;	" "	= 1.30
Point c	— 25 "	peaked wave;	" "	= 1.56
" d	— 25 "	sine wave;	" "	= 1.41

of full charge, provided, of course, that the leakage is low. If the valve in series with the voltmeter is short-circuited, the voltmeter will read r.m.s. values; but these values will depend not only upon the above ratio but also upon the capacitance of the voltmeter as well.

If the apparatus is used directly on a step-down voltage transformer or on voltmeter coils without multiplier, the ratio of the reading of the voltmeter with the valve in series to its reading with the valve short-circuited will give at once the crest factor of the wave.

An important advantage is that the pointer of the voltmeter does not return at once when the voltage is removed. For instance, if the dielectric under test is punctured and the voltage drops, the reading of the voltmeter taken a moment after puncture has occurred will show the voltage which caused the puncture. Hence the voltmeter does not need to be watched so minutely during test as in the case when the indications follow directly any drop in the testing voltage.

This arrangement has been tested in a number of different ways, but the most important ones are summed up in the curves of Fig. 5, together with the appended table. Wave form A was built up from a sine wave fundamental plus a third harmonic; wave form B represents the fundamental alone, and wave form C represents a peaked wave built up from the third and fifth harmonics. The crest factors of the various waves were calculated from the wave forms as traced by a wave meter and were determined also by using a wave meter as a crest voltmeter and an ordinary voltmeter to give the r.m.s. values. These figures may be compared with the crest values as given by the valve voltmeter in which r.m.s. value was obtained by short-circuiting the valve. It will be seen that the degree of agreement is a very satisfactory one, indicating that with these wide variations of crest factor, the crest voltmeter gave true indications. The frequency was 60 cycles per second.

In a further series of tests the electrostatic voltmeter was replaced by a sensitive unipivot galvanometer in series with a resistance of one megohm, and in parallel with a condenser of one microfarad. The indications of the galvanometer were taken with frequencies of 25 and 60 cycles per second. In Fig. 6 is shown the relation between crest voltage as indicated by the electrostatic voltmeter plus the valve and the galvanometer plus condenser and valve. It will be seen that the relation between the two is practically a constant one, independent of the frequency of the current, which indicates that a galvanometer if looped about a sufficient capacitance may be used instead of the electrostatic instrument. Inasmuch as the latter instrument has, in some respects, less desirable characteristics than a galvanometer, particularly in respect to damping, the latter connection may be found in practise to be the more desirable one. The calibration of the latter arrangement, however, would be rather less direct than that of the former.

In conclusion it may be noted that the arrangement given offers possibilities in the matter of the study of surges. If it were connected through suitable transformers to a cable and a proper balance of valve capacity and capacitance were used, the apparatus might be adapted to trapping either a current or a voltage surge, and indicating the maximum value of the surge. With the capabilities of the arrangement for retaining its indication, it is probable the electrostatic voltmeter might be fitted to operate as an intermittent recorder, and so leave a record on a chart of the surges which have come in during a certain period of time or during the course of certain operations.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

THE CREST VOLTMETER

BY L. W. CHUBB

ABSTRACT OF PAPER

The demand for testing dielectric media in terms of crest voltage has resulted in several schemes of measuring high voltage. The paper mentions and compares some of the methods of high-voltage measurement and describes in more detail the crest voltmeter which has been found to be more satisfactory in commercial testing than the spark gaps which have been adopted by the Institute in the Standardization Rules. The construction, operation, accuracy and applications of the crest voltmeter are briefly described. The present Standardization Rules for the measurement of high testing-voltages recommend spark-gap methods which under certain conditions are impractical, inconvenient, and dangerous. The summary states that the spark gaps should be only a calibrating standard and a more practical instrument, such as described, the preferred working standard.

WITHIN the last few years the importance of making careful dielectric tests of insulation has been emphasized and several papers have been presented which deal with meters and apparatus for adjusting and reading the value of the testing voltage in high-voltage testing circuits. It is the purpose of this paper to describe a late modification of such a meter, to compare it with the sphere spark gap adopted as a standard by the Institute, and mention the relative merits of some of the common means of measuring high voltage in practical testing.

At ordinary frequencies, breakdown of dielectric media is dependent more upon the crest or maximum value than the r.m.s. value of the voltage wave, and for commercial testing it is desirable to have quick and accurate means of measuring voltage, which will give an indication proportional to the crest value of the testing wave under testing conditions. A meter for this purpose should preferably derive its voltage from the high-tension winding. It should be convenient, safe, direct reading, independent of atmospheric conditions and cause no oscillatory disturbances which will damage apparatus under test.

The needle and sphere spark gaps are the crest voltmeters which have been adopted by the Institute as a working stand-

ard. Careful calibrations of the spark gaps have shown that between certain limits and at commercial frequencies they give accurate indications of crest voltage when the necessary corrections for temperature, barometric pressure and humidity are made.

The possible accuracy of the spark gap, however, is not sufficient justification for its use in commercial testing, for it meets none of the other important requirements.

Other voltage measuring means, corrective schemes and types or modifications of crest voltage indicators have been described[1] from time to time, some of which meet the requirements.

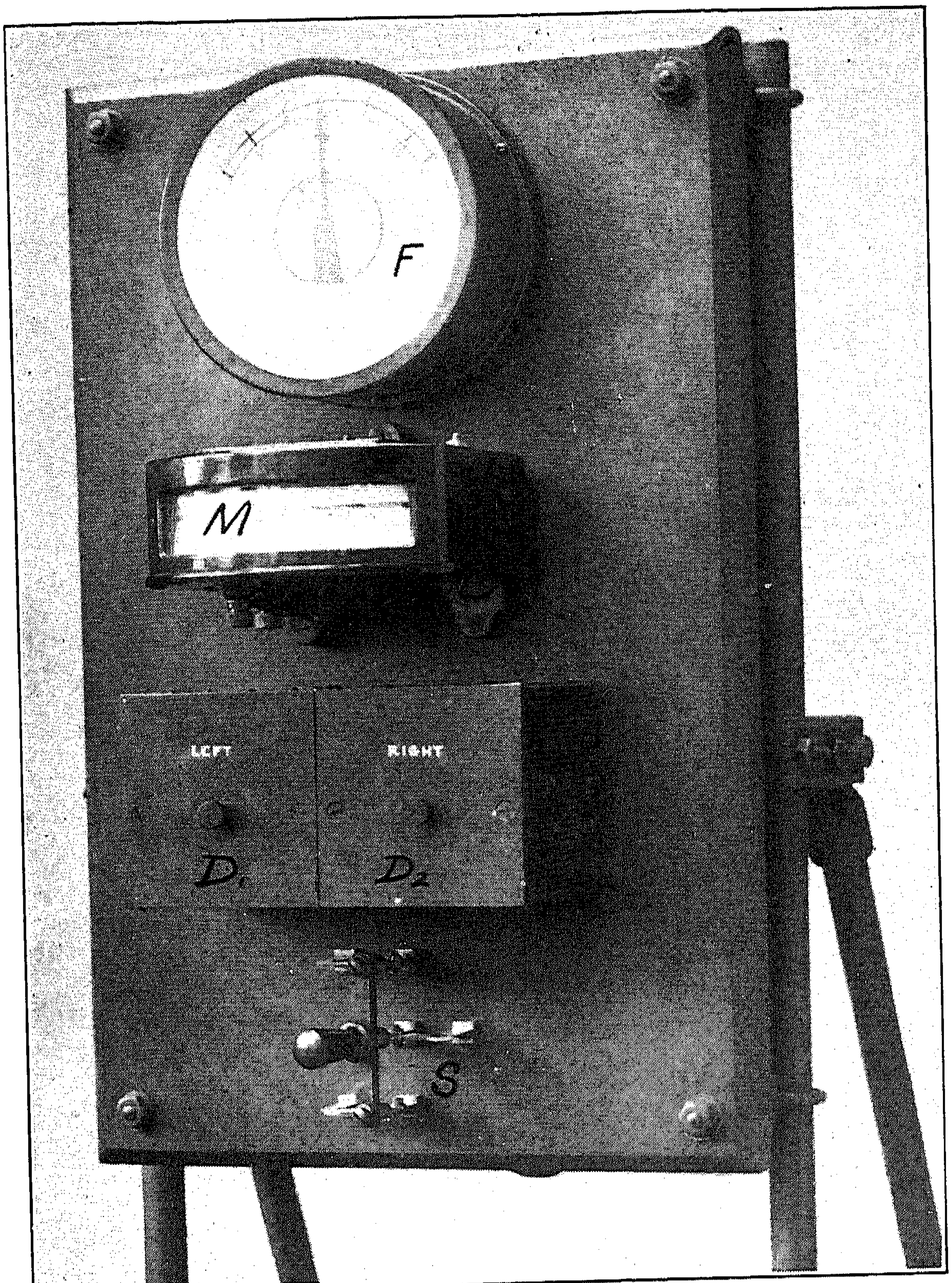
Direct measurement of high-tension voltage with the electrostatic voltmeter and derivation of high-tension voltage from the primary voltage, from auxiliary ratio transformer, from tertiary coil placed in the transformer or from section taps on the secondary winding have been the most common methods used. Generally r.m.s. voltage is read, assuming the voltage wave to be sinusoidal. When testing apparatus of high capacitance and at high voltage, the ratio of transformation is affected and the wave is often so distorted that corrections for ratio and crest factor should be made. With some of these methods, and under certain favorable conditions with all of the methods, corrections can be made, but in the majority of cases such corrections are too laborious or too much in error to be worth while.

In former papers schemes of correction for crest factor have been given. Some of these have since been combined with certain improvements into an instrument especially suited to dielectric testing, equally accurate and very much more practical than the spark gap.

The Crest Voltmeter

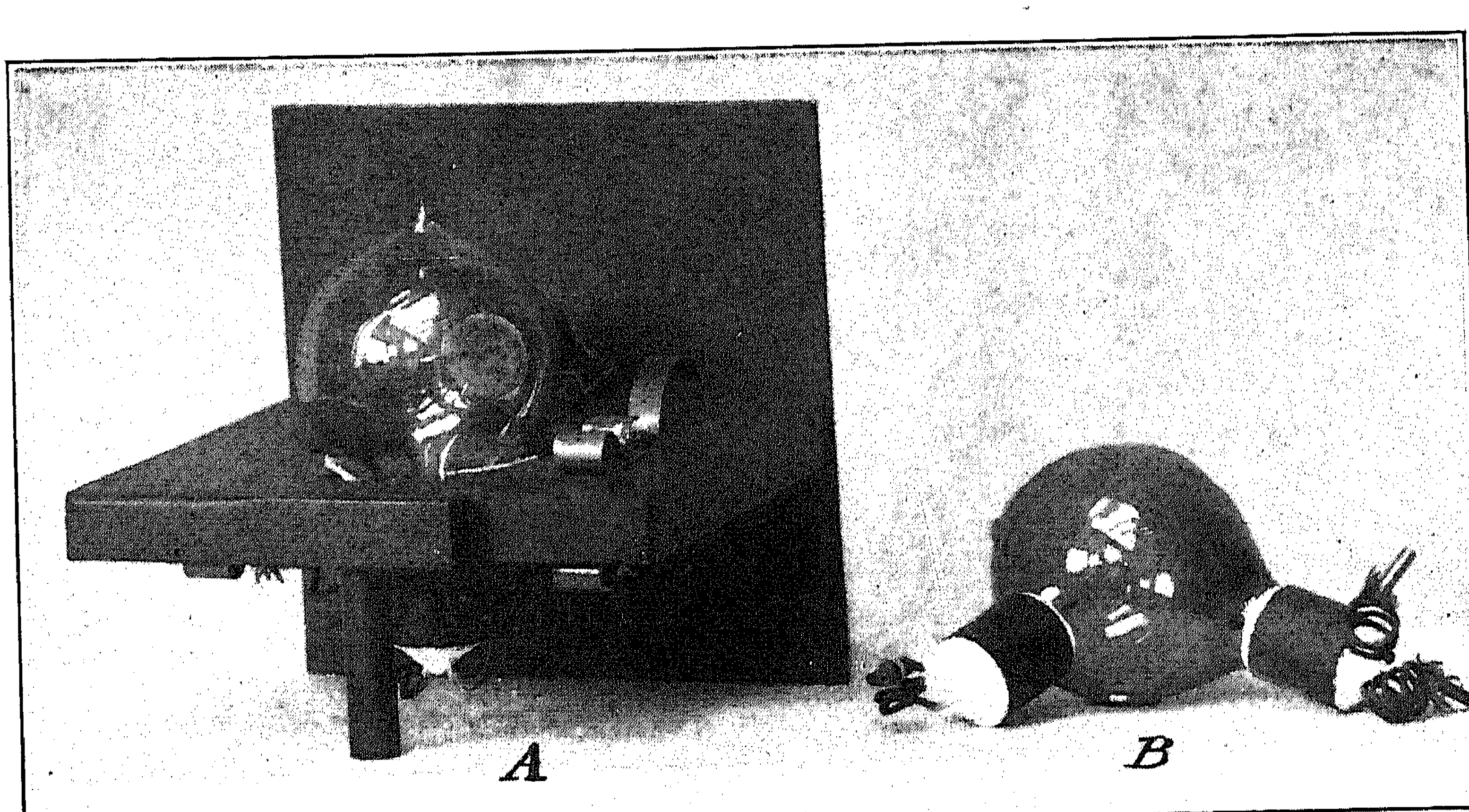
Historical. In a paper[2] on the calibration of the spark gap, an absolute method of measuring the crest of an alternating voltage wave was described. By means of a rotating contactor and d'arsonval galvanometer, or d-c. voltmeter, the charging current to a guarded air condenser was integrated and from it the peak values of a symmetrical voltage calculated. In some

1. Sharp and Farmer, Trans. A.I.E.E., Vol. XXXI, 1912, p. 1617.
Chubb and Fortescue, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739.
Whitehead, Trans. A.I.E.E., Vol. XXXII, 1913, p. 1737.
Whitehead and Gorton, Trans. A.I.E.E., Vol. XXXIII, 1914, p. 951.
Middleton and Dawes, Trans. A.I.E.E., Vol. XXXIII, 1914, p. 1185.
2. Chubb and Fortescue, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739.



[CHUBB]

FIG. 1—CREST VOLTMETER



[CHUBB]

FIG. 3

A—Hot cathode valve mounted in self-connecting drawer.
B—Hot cathode valve disconnected.

later work, Whitehead and Gorton substituted mercury arc rectifiers for the rotating contactor and the Moscicki type of condenser of measured capacitance for the air condenser of figured capacitance. The change from the mechanical rectifier was made to allow measurement at high frequency and to the glass condensers presumably for convenience. In the latest modification, described in this paper, the hot cathode tube is substituted for the mercury arc rectifier and the whole apparatus arranged in compact form to make a practical measuring instrument for the testing department or laboratory.

Construction. Fig. 1 shows one type of instrument mounted on a small panel to be placed near the control apparatus of the testing transformer. It consists of a permanent magnet instrument (M) sensitive to low currents, two small hot cathode

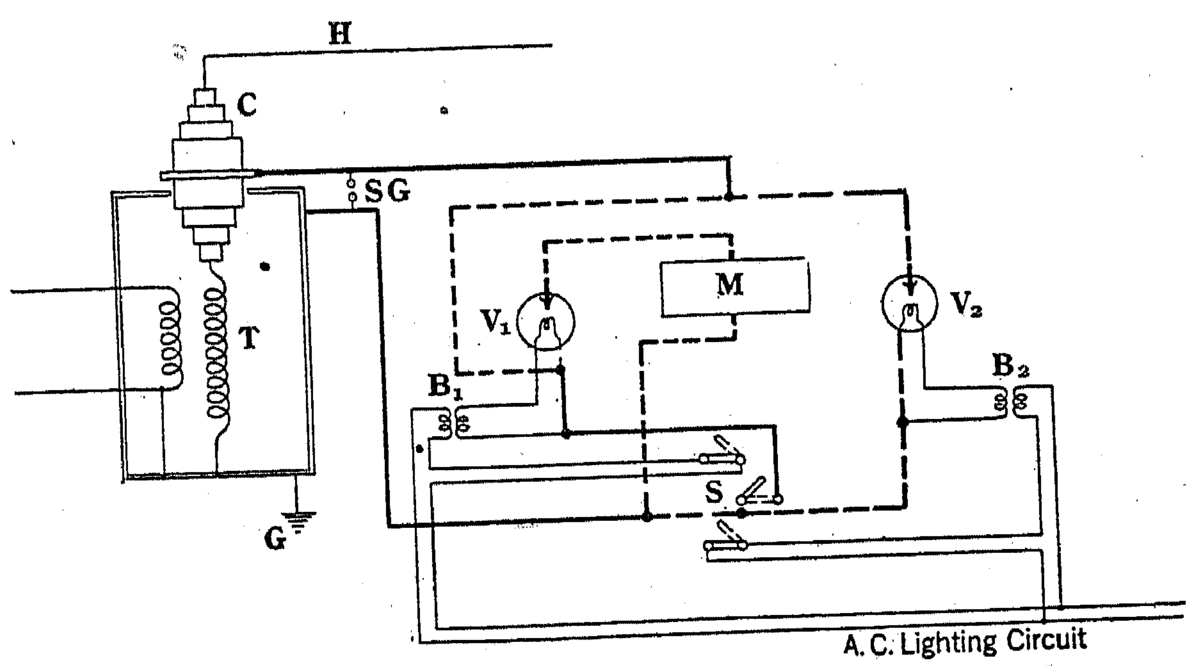


FIG. 2

valves mounted in the drawers (D_1D_2), a frequency meter (F), an exciting switch (S), and on the back the necessary wiring, resistors and two bell-ringing transformers for heating the cathode filaments of the valves.

The high-tension condenser terminal of the transformer or other separately mounted condenser is used in connection with the meter panel. When the transformer terminal is used, it is insulated from ground and the crest voltmeter is connected between ground and the outside flange of the terminal.

Fig. 2 shows the diagram of connections, in which T is the testing transformer diagrammatically shown in a grounded case; C is a condenser terminal used to bring out the high-tension lead (H); V_1 and V_2 are two rectifiers or valves shown in detail in Fig. 3 and having an anode of tungsten or molybdenum and

a cathode of incandescent tungsten working in an atmosphere of mercury vapor, or one of the noble gases at low pressure. The filamentary cathodes are heated by the secondary current from two bell-ringing transformers, B_1 and B_2, the primaries of which are connected to any suitable a-c. lighting circuit; M is a permanent magnet indicating instrument connected in the anode lead to the valve V_1; S is three single-pole switches operated with a single handle and used to close the cathode heating circuits or short-circuit the instrument when not in use; $S.G.$ is a safety gap between the leads to the meter to protect the insulation of the apparatus in case of interruption in the supply to the bell-ringing transformers when the switch is in the working position, or in case of an accidental open circuit in the instrument wiring. The frequency meter shown in Fig. 1 is not an essential part of the measuring apparatus but may be included to make a proportional correction when the frequency varies appreciably from normal.

Operation. The condenser terminal or other condenser connected to the high-tension lead takes a charging current at all times proportional to the differential or rate of change of voltage across its terminals. At both the positive and negative maxima of the voltage waves this current is zero and the time integral or area of the current wave between these zero values is a direct measure of the difference between the maximum and minimum voltages. On account of the asymmetrical conduction of the cathode valves, the arrangement of circuits shown in Fig. 2 is such that the charging current in one direction passes through the instrument M and the valve V_1 as shown by the heavy dotted line. Current in the opposite direction passes through the valve V_2 without passing through the meter, as shown by the heavy broken line. The light lines in the figure represent the primary and secondary exciting circuits for the cathode filaments fed from the lighting circuit. When the meter is not in use the switch is thrown to the right, which short circuits the apparatus and opens the primary circuits of the exciting transformers.

The torque of a permanent magnet meter is proportional to the average value of the current passing through it, and since for waves of constant length the area is proportional to the average height of the current, it is evident that the meter will give an indication proportional to the time integral of the pulsating current through the valve V_1 and this will in turn be proportional to the crest of the voltage wave.

Calibration. The instrument is calibrated in parallel with the standard spark gaps or another standardized crest voltmeter and usually the scale drawn so that it indicates the r.m.s. value of a sine wave having a crest value equal to that of the voltage wave to which it is connected. When thus calibrated it is the equivalent of the needle or sphere gap.

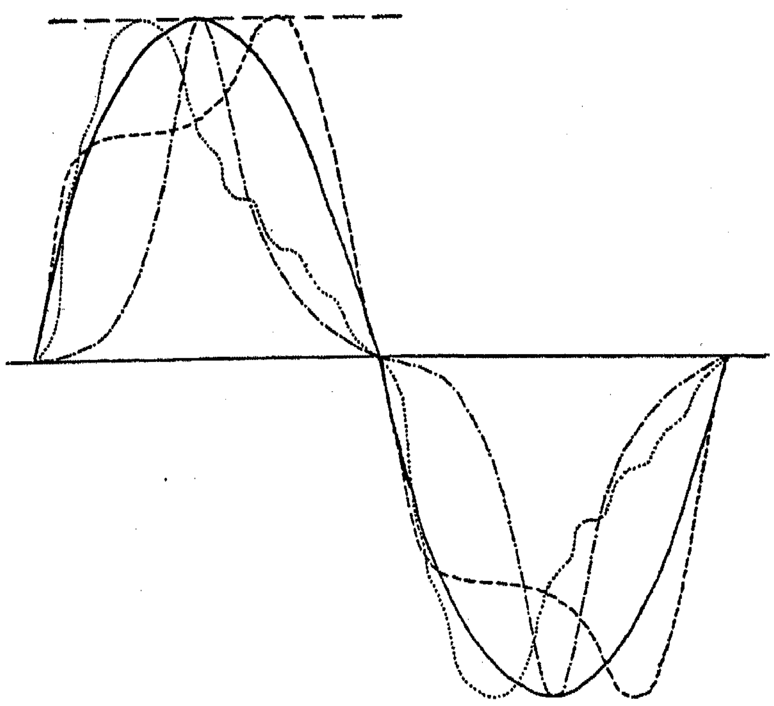


FIG. 4

Accuracy and Corrections. With the rotating contactor commutating at symmetrical zero points in the current wave, the indication of the instrument is theoretically correct with all wave shapes containing only odd harmonic components at the fundamental frequency at which it was calibrated. On unsymmetrical voltage waves containing even

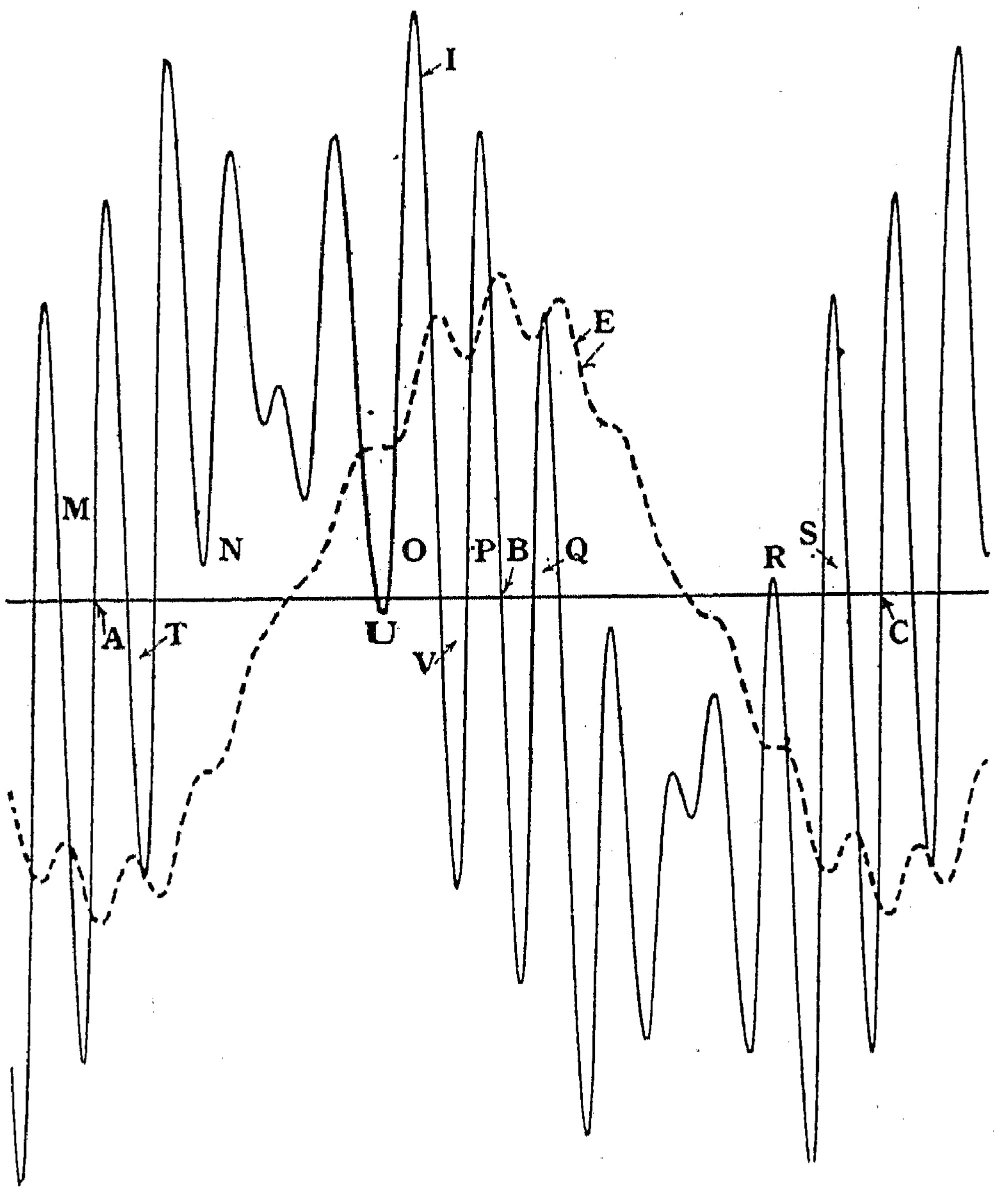


FIG. 5

harmonic components (which seldom, if ever, exist in testing work) the instrument will indicate the mean between the positive and negative crest values.

With the rectifier valves, any of the waves of Fig. 4 will give the same indication and the crest voltmeter will give a theoretically correct reading. With waves having more than one maximum and one minimum per cycle there will be an error depending upon the depth and number of ripples in the wave. Fig. 5 shows in the dotted curve a voltage wave having a high-frequency ripple placed to give a large error in the meter indication. This wave has seven maxima and seven minima per cycle. The irregular full line wave is the differential of the voltage and represents the condenser current. The time integral of the current wave between the zero points, A and B, corresponding to the positive and negative crest values of the voltage wave, is a measure of the crest value. This integral contains the positive areas M, N, O and P and the negative areas T, U and V. Theoretically, all current, both positive and negative, between the points A and B should pass through the meter and no current between the points B and C should pass through the meter. Reverse currents cannot pass through the valves, so that the meter will integrate all positive current area and neglect all negative area. At first sight it is evident that this will cause an appreciable error. Table I shows that in this extreme case the error is 26 per cent.

TABLE I

Showing comparison between correct time integral of the current wave of Fig. 5 as obtained with the rotating rectifier and the result obtained with hot cathode rectifier.

Area	With rotating rectifier		With hot cathode rectifier	
	+	—	+	—
M	0.40		0.40	....
T	....	0.22	....	....
N	2.54	....	2.54	....
U	....	0.00	....	....
O	0.74	....	0.74	....
V	....	0.25	....	....
P	0.44	....	0.44	....
Q	....	....	0.22	....
R	....	....	0.00	....
S	....	....	0.25	....
Sum	4.12	0.47	4.59	0.00
Net	3.65	....	4.59	....

Tooth ripples and resonant ripples, such as shown in the voltage wave of Fig. 5, are infrequent and can be entirely avoided by the use of proper means in the transformer circuits.

In careful tests on steady circuits of different wave shapes the indications of the spark gap, corrected for atmospheric conditions, have shown agreement and duplication of points to within 0.15 per cent. Such tests seem to indicate that the capacitance of the condenser terminals used is independent of the wave shape. The capacitance is, however, a function of the voltage and increases 4 or 5 per cent between low voltage and 25 per cent over voltage. This variation of condenser capacitance with voltage, however, causes no error, as it is taken care of by the instrument calibration.

The indications vary directly with frequency and proportional corrections can be made if the frequency varies from normal. If it is desirable to eliminate frequency corrections, a calibrated shunt resistance to the meter M is used and adjusted to the indication given by the frequency meter. This complication is not justified, however, as frequency variations are infrequent and the correction when necessary is very simple.

Applications. The crest voltmeter has been found to fulfill all of the requirements of a practical instrument for dielectric testing, and for reading the crest value of pulsating and alternating voltage in the laboratory. Since its indications are a measure of the difference between maximum and minimum values of a periodic voltage wave, pulsating waves starting from zero can be read or unsymmetrical waves can be read if one of the crest values is known.

Summary

1. The crest voltmeter is a direct-reading instrument, reading either the r.m.s. value of a sine wave having the same crest as a high voltage wave to which it is connected, or the true crest value, depending upon its calibration.

2. The indications of the instrument are independent of atmospheric conditions and require no corrections except a proportional correction for variations from normal frequency.

3. The instrument is the equivalent of the sphere spark gap and derives its voltage from the high-tension circuit.

4. The indications are theoretically correct for all distorted waves having not more than one maximum and one minimum value per cycle, and practically accurate for all other commercial wave shapes to be found.

5. The instrument gives a continuous indication during the application and adjustment of voltage, instead of a limiting indication similar to that of the spark gap.

6. No preliminary setting with load disconnected need be made, as the voltage may be read under testing conditions.

7. The instrument is safe, convenient, and does not cause spark surges.

8. Tests with the spark gap in accordance with sections 531 and 532 of the Standardization Rules are impractical, inaccurate and destructive under certain conditions, while with the crest voltmeter all such tests can be practically and satisfactorily made.

9. The standard spark gaps should be the primary standard for calibration only, in accordance with section 534 of the rules, and the crest voltmeter or its equivalent should be used as a secondary and working standard.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

THE VOLTMETER COIL IN TESTING TRANSFORMERS

BY A. B. HENDRICKS, JR.

FOR EXACT determination of the high-tension voltage in testing transformers, an auxiliary winding of few turns placed on the same core and connected to an accurate voltmeter has been used with success.

This method was advocated and the construction explained some years ago,* but the idea seems to be generally misunderstood, the accuracy of the result obtained being often questioned.

For precise results at all loads and power factors, it is necessary and sufficient that the ratio of the flux linkages of the voltmeter coil and the high voltage winding be a constant.

The flux here considered is the resultant flux linked with the high voltage winding, or the main flux plus or minus the leakage flux combined vectorially.

With the coil so placed, the *IR* drop is the only sensible error. This is usually small, and owing to the vector relationship under ordinary loads is practically negligible.

It is not advisable to compensate for this by the position of the voltmeter coil, as the correction would be exact for one value of load and power factor only.

The impedance of the voltmeter coil itself may be neglected.

The accuracy of the method depends entirely on the design of the transformer and the location of the voltmeter coil, and can be made almost perfect.

Ordinarily, a dynamometer type of voltmeter is used, indicating effective values. If the maximum value is desired, a sine wave of potential must be employed or, the maximum determined by other means, such as an oscillograph.

It is suggested that much difficulty may be eliminated by the use of a true sine wave generator, and the avoidance of regulating devices and transformer characteristics liable to distort the wave.

*High-Tension Testing of Insulating Materials, A. B. Hendricks, Jr., TRANS. A. I. E. E. Vol. XXX, 1911, p. 167.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 8, 1916.

NOTES ON THE MEASUREMENT OF HIGH VOLTAGE

BY WILLIAM R. WORK

ABSTRACT OF PAPER

A briet account is given of some experiments made to determine the relative accuracy of certain methods used in measuring high voltages.

The methods comprise the use of a tertiary (or voltmeter) coil in the high-tension transformer, the direct measurement of voltage by a crest voltage meter and the derivation of the high-tension pressure from the primary voltage.

IN MOST commercial and experimental tests employing high voltage a knowledge of the crest or peak value of the voltage is of the first importance. Often this crest value may be determined quite satisfactorily by a gap method. In other cases (dielectric tests on cables, etc.,) the use of a spark-gap is not desirable because the discharge of the gap may set up oscillations which will over-stress the dielectric thereby permanently injuring or even puncturing it.[1] There are other well known disadvantages attendant on the use of a spark-gap as a voltmeter. Several methods for the measurement of high voltages which are free from the objections peculiar to the spark gap have been used.

This paper is an account of some tests which were made with the view of comparing these methods among themselves and with a spark gap.

EXPERIMENTAL APPARATUS

The generator used is a 60-kv-a., 250-volt, eight-pole, 60-cycle, three-phase alternator with both ends of each phase winding brought out to the terminal board. In these tests the excitation was kept substantially constant at normal value and three schemes of connection were used giving three different classes of voltage waves. These schemes will be designated *Supply A*, *Supply B* and *Supply C* respectively.

1. *Voltage Testing of Cables*, Middleton and Dawes, TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 1185.

Supply A. Windings connected in Y. Wave shape approximating a sine form. See Fig. 1.

Supply B. One-phase winding alone. Prominent third harmonic with other harmonics giving a flat-topped wave. See Fig. 1.

Supply C. Two windings connected in V. Same fundamental as *Supply B* but the third and ninth harmonics are doubled in value and the wave has a prominent hollow at the quarter-cycle point. See Fig. 2.

The transformer has a capacity of 100 kv-a. at 200,000 volts, 60 cycles. One end of the high-tension winding was grounded. The primary winding consists of four separate 480-volt coils arranged to be connected in parallel, in series-parallel or in series. The reactance drop is about 4.5 per cent, the resistance

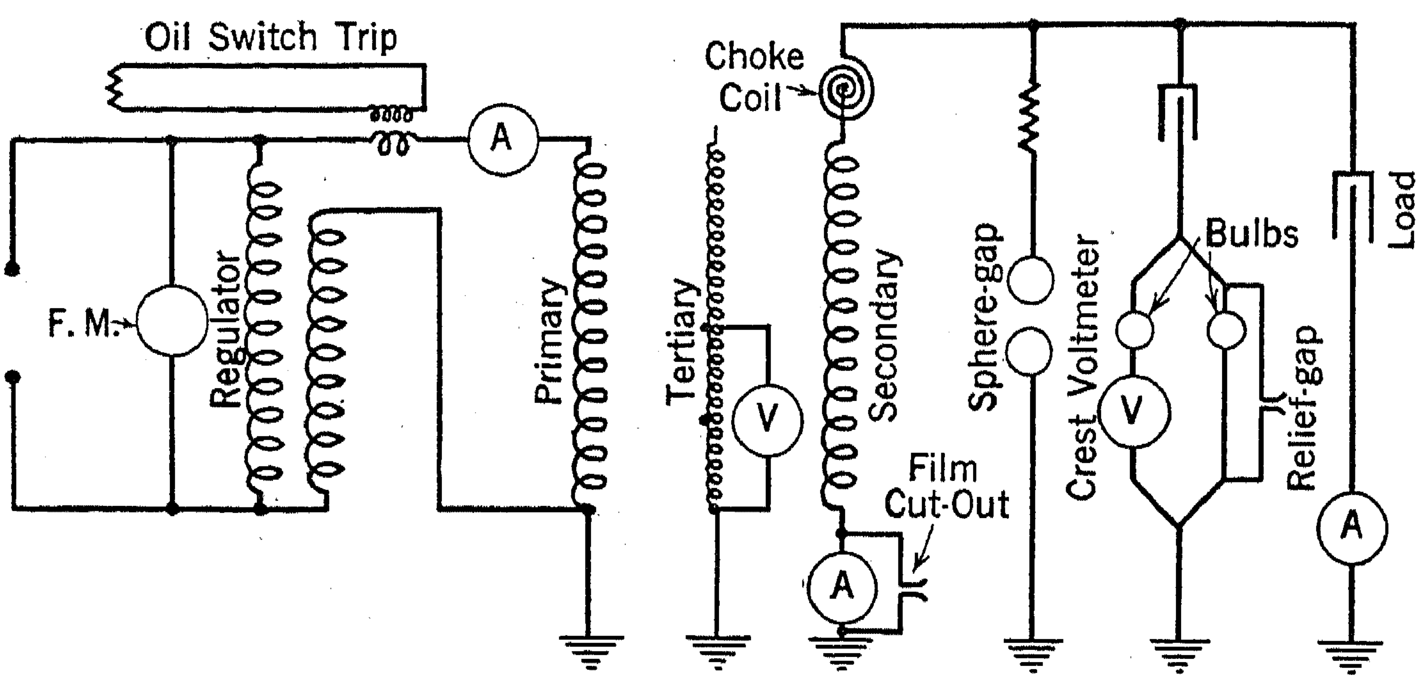
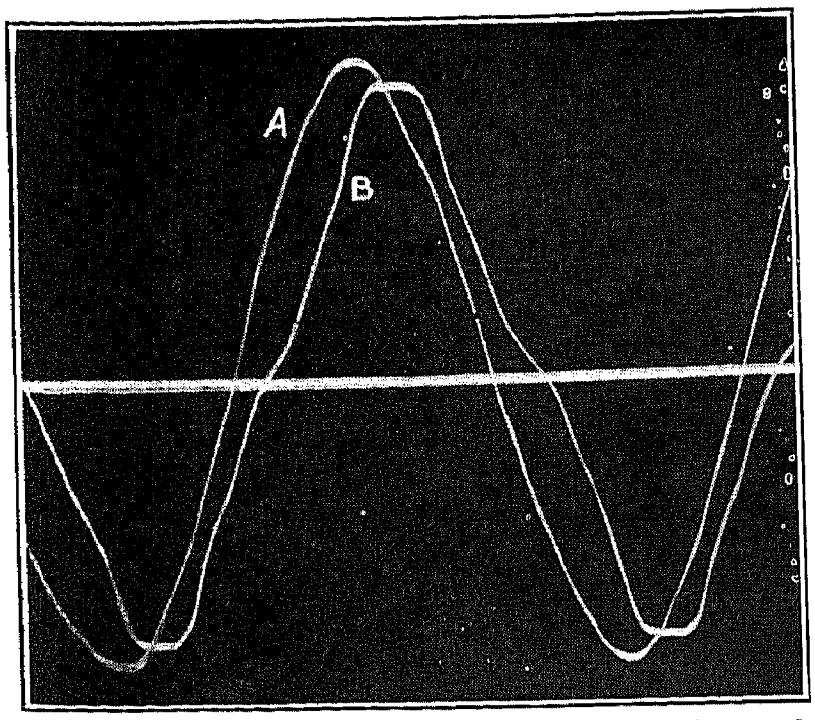


FIG. 4

drop about 0.6 per cent. Due to the capacitance of the high-tension winding the no-load power factor of the transformer is high, varying from about 99 per cent to about 96 per cent, over the range of voltage used in these tests. The transformer had been equipped with a tertiary, or voltmeter, coil intended to serve as a means of determining the secondary voltage. This coil has taps brought out at 25 per cent and at 50 per cent of the winding. The accuracy with which the secondary voltage could be determined by the use of this coil was one of the things investigated.

Control of the voltage was obtained by a 50-kv-a., 60-cycle induction regulator with which the pressure applied to the transformer primary could be varied from zero to twice the generator voltage in a satisfactory manner.



[WORK]

FIG. 1—NO-LOAD WAVE FORMS OF SUPPLIES A AND B

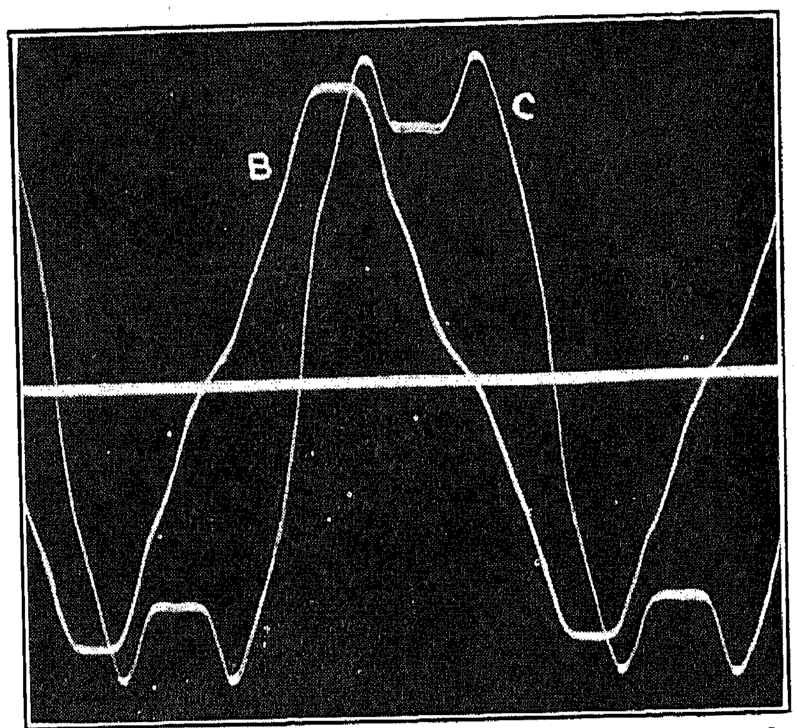


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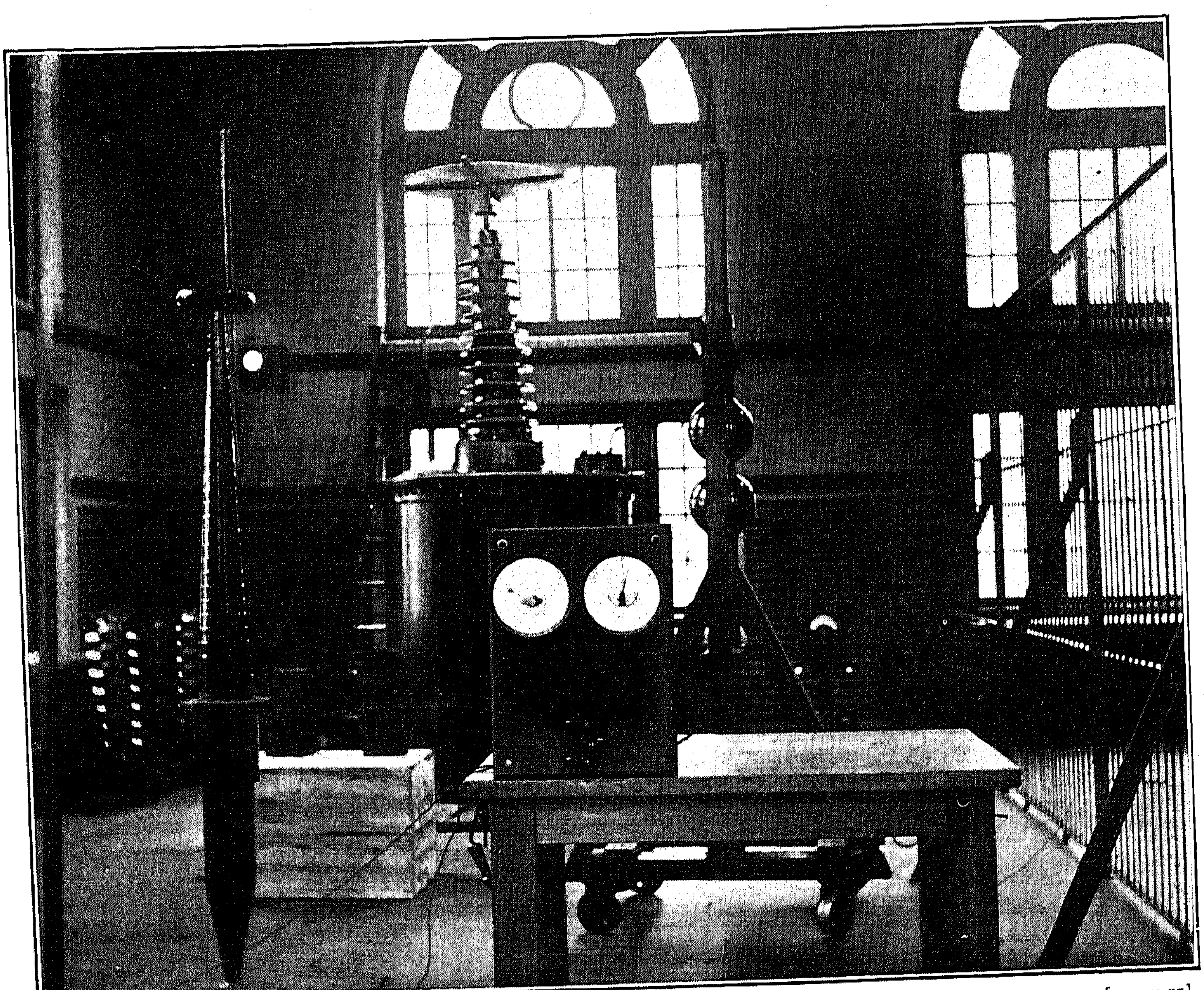
FIG. 2—NO-LOAD WAVE FORMS OF SUPPLIES B AND C



[WORK]

FIG. 3—TRANSFORMER, SPHERE GAP AND CREST VOLTAGE METER

Voltmeters of the electrodynamometer type were used, all being checked against the same precision voltmeter. The larger secondary currents were measured by a hot-wire ammeter; smaller currents, by voltmeters used as ammeters.

For the tests with condensive load, sixty $\frac{1}{4}$-mf., 2000-volt condensers were available. These were used in two different combinations, *viz.*, all in series, and thirty in series, two in parallel.

The actual secondary voltage was determined by a standard 250-mm. sphere gap. The relation between the length of gap and voltage and the correction for air density as specified in the Standardization Rules of the Institute were used. Incidentally, the air density correction factor, k, for 250-mm. spheres, corresponding to a barometric pressure of b mm. and an air temperature of t deg. cent., can be expressed as a function of b and t thus:[2]

$$k = \frac{0.366\, b}{273 + t} + 0.066$$

In most of the tests the gap was set at a certain length and the voltage slowly raised until spark-over occurred; in some cases, however, the gap was shortened slowly with the voltage constant. There was little difference in the results obtained by the two methods of manipulation although the first method gave slightly more consistent results and was therefore preferred. In using the gap a set of observations was considered good only when the voltmeter (on the tertiary coil) indicated stable conditions at the moment of breakdown. Each point is the mean of five to seven trials.

Determination of Crest Factors

Polar oscillograms of the voltages and currents were taken and the first six odd harmonic components of the waves were determined by a mechanical analyzer.[3] The crest values were then obtained by calculating the ordinates of the waves at a few degrees on either side of the angle at which an inspection of the oscillogram indicated the peak. The crest values thus determined from the harmonic components were checked by direct measurement of the amplitudes on the oscillograms.

2. Derived from Peek's eq. (4), p. 931, Trans. A.I.E.E., Vol. XXXIII, 1914.

3. *Electric Journal*, Feb. 1914, May, 1914.

TABLE I—SECONDARY VOLTAGE DERIVED FROM TERTIARY VOLTAGE

(Secondary pressure derived from the observed tertiary voltage and expressed as the r. m. s. value of the sine wave of equal peak.)

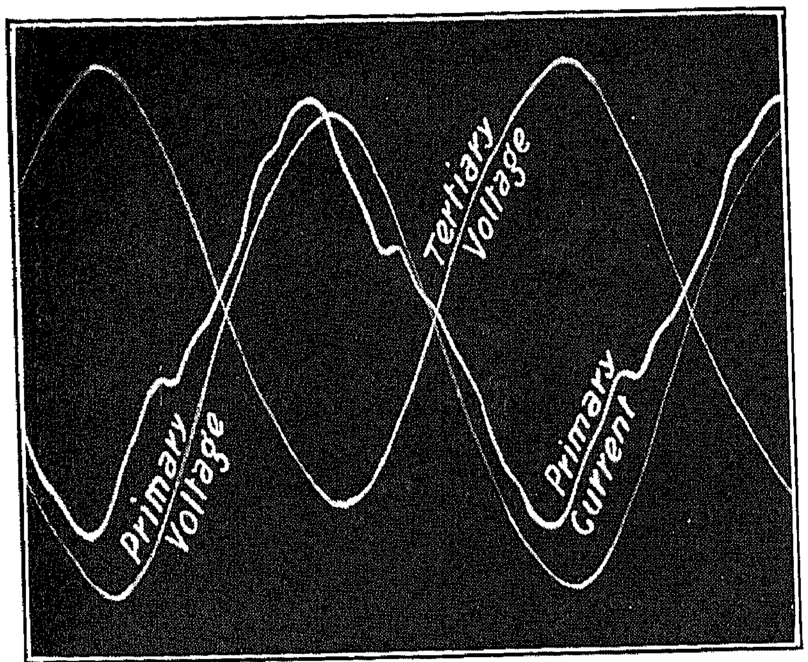
Ratio of secondary turns to tertiary turns = 1000 : 1

Test	1	2	3	4	5	6	7	8
Supply	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*
Secondary current (amp.)	0.024	0.035	0.114	0.342	0.031	0.110	0.0306	0.323
Tertiary r. m. s. volts × 1000 = E_3	99,300	95,400	68,900	59,000	86,000	63,300	56,100	48,600
Crest factor of tertiary voltage ÷ $\sqrt{2}$ = F_3	1.026	1.024	1.011	0.968	1.127	1.067	1.017	1.212
R. m. s. value of sine of equal peak of ter. volts × 1000 = $E_3\ F_3$	101900	97,700	69,700	57,100	96,900	67,500	57,100	58,900
Secondary volts by gap. R. m. s. value of sine of equal peak = E_2	103700	96,900	69,300	57,600	96,600	67,400	57,900	57,600
Per cent error by (*a*) r. m.s. ter. volts alone	—4.2	—1.5	—0.6	+2.4	—11.0	—6.1	—3.1	—15.6
(*b*) ter. volts corrected for crest factor	—1.7	+0.8	+0.6	—0.9	+0.3	+0.2	—1.4	+2.3
Figures	5	6	7	8, 13	9	10	11, 14	12, 15

An inspection of the above data shows that the tertiary voltage *corrected for crest factor* is a satisfactory measure of the actual secondary voltage as determined by a sphere gap.

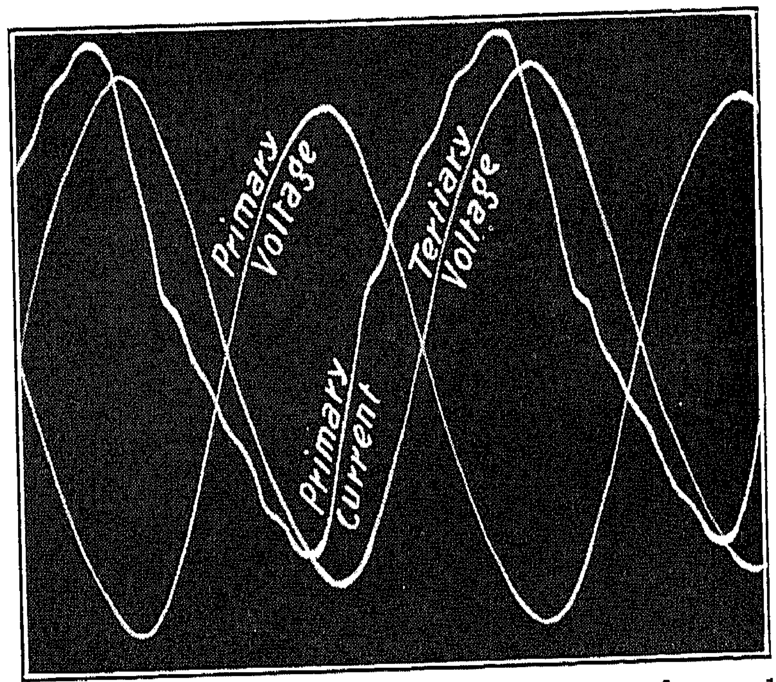
Obviously the r.m.s. value of the tertiary voltage should not be used alone as a measure of the secondary voltage, when the latter is defined in terms of the crest value, unless something is known about the crest factor. The wave shape of the secondary voltage depends upon so many factors of complex relationship that it is practically impossible to predict how the crest factor will be changed by a given change in the conditions of load or supply. The condensive character of the usual load in combination with one or more of the several inductances of the system may result in the amplification of one of the higher harmonics through partial, if not full, resonance, or it may result in suppression of the higher harmonics. Magnetic saturation in the generator, control apparatus and the transformer plays an important part in wave distortion, while corona, by changing the value and phase of the current, may contribute to the effect through generator reactions.

In this connection it is interesting to study the oscillograms and the crest factors of the voltage waves. In tests 1 to 4 (Figs. 5 to 8) the generator was connected to give a "good" e.m.f. wave (Supply *A*). As the load was increased the tertiary voltage wave shape changed from a peaked form to a



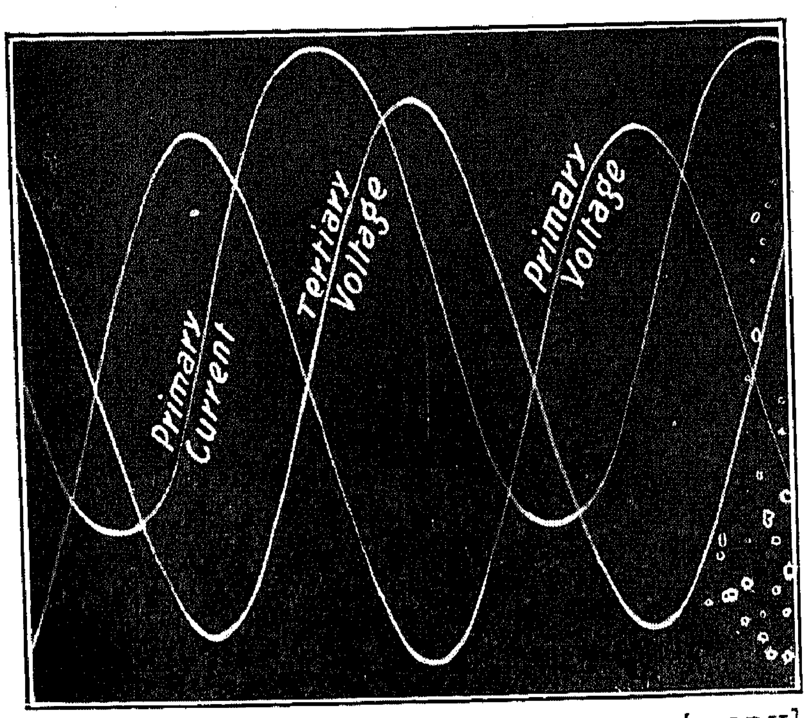
[WORK]

FIG. 5—TEST No. 1
Crest factor of primary voltage = 1.421
Crest factor of tertiary voltage = 1.451



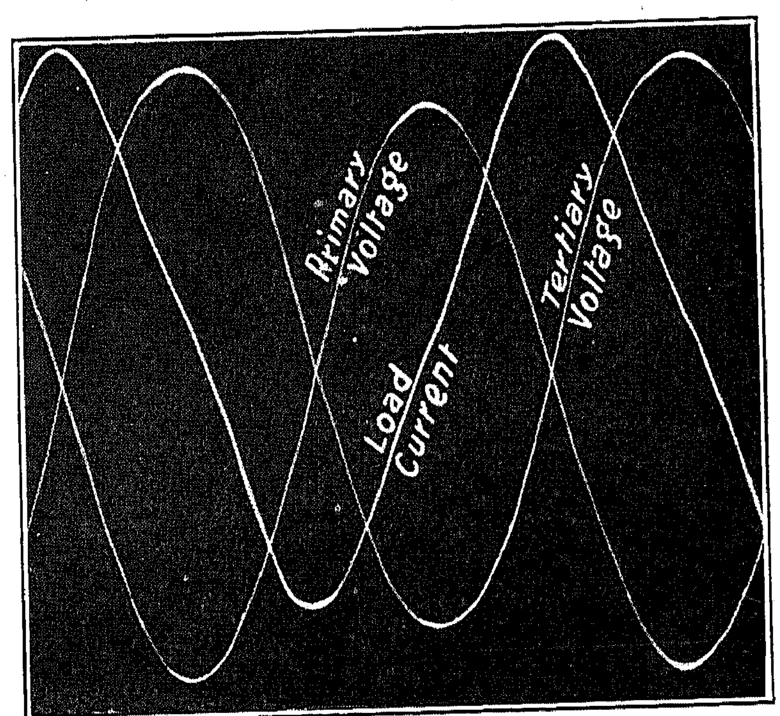
[WORK]

FIG. 6—TEST No. 2
Crest factor of primary voltage = 1.434
Crest factor of tertiary voltage = 1.448



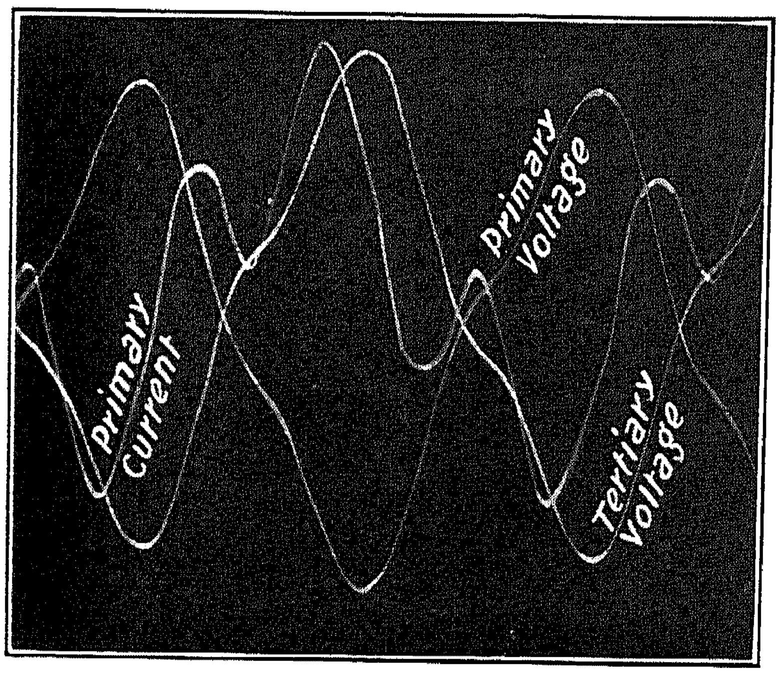
[WORK]

FIG. 7—TEST No. 3
Crest factor of primary voltage = 1.424
Crest factor of tertiary voltage = 1.430



[WORK]

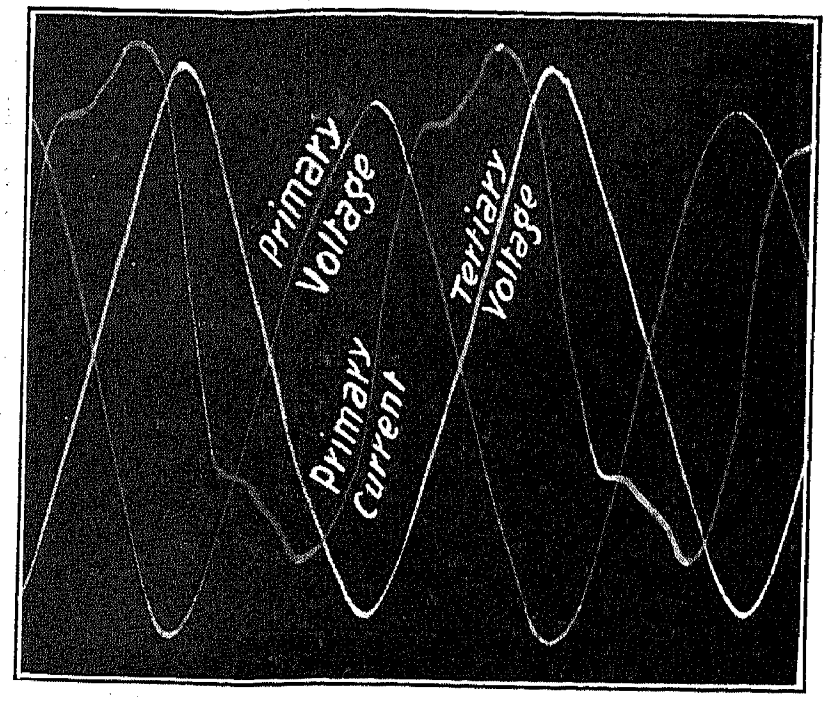
FIG. 8—TEST No. 4.
Crest factor of primary voltage = 1.414
Crest factor of tertiary voltage = 1.369
Crest factor of integral of load current = 1.373



[WORK]

FIG. 9—TEST NO. 5

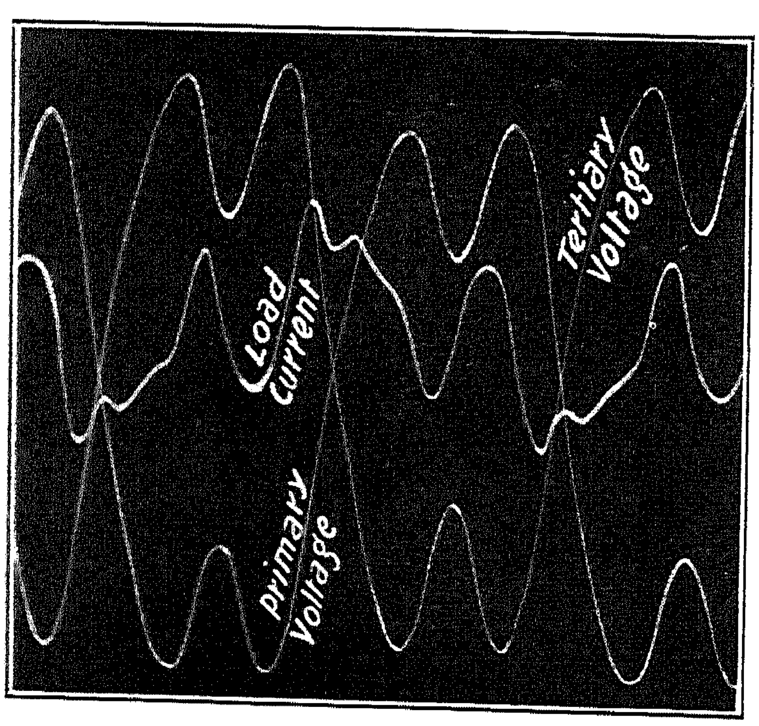
Crest factor of primary voltage = 1.581
Crest factor of tertiary voltage = 1.593



[WORK]

FIG. 10—TEST NO. 6

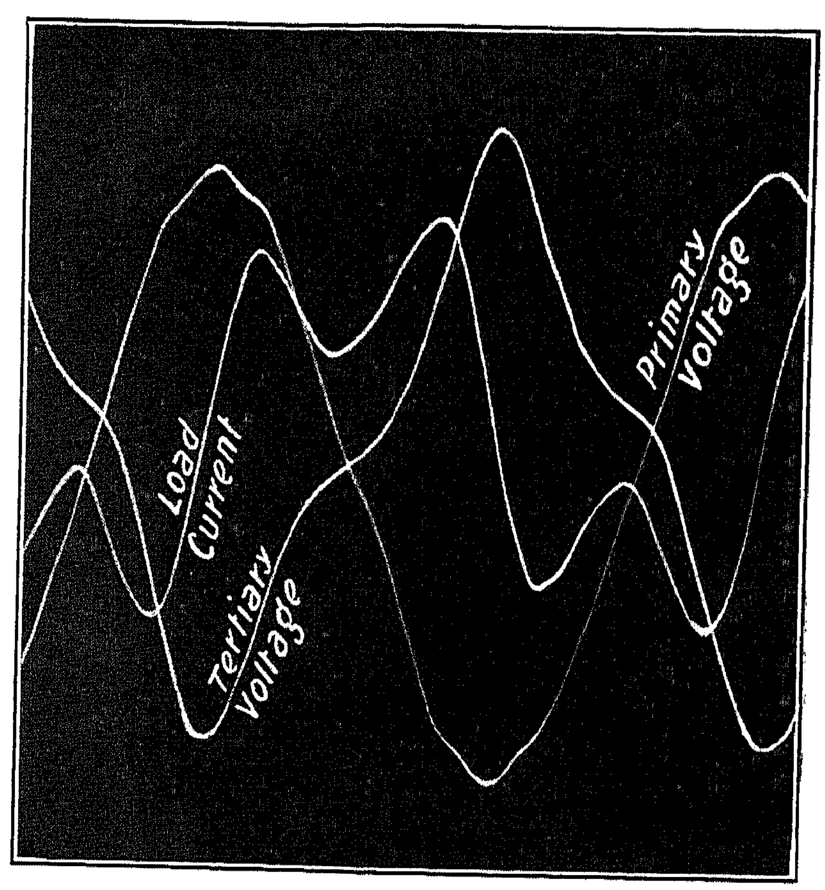
Crest factor of primary voltage = 1.474
Crest factor of tertiary voltage = 1.509



[WORK]

FIG. 11—TEST NO. 7

Crest factor of primary voltage = 1.399
Crest factor of tertiary voltage = 1.438
Crest factor of integral of load current = 1.528



[WORK]

FIG. 12—TEST NO. 8

Crest factor of primary voltage = 1.437
Crest factor of tertiary voltage = 1.714
Crest factor of integral of load current = 1.655

flat-topped form, the crest factor varying apparently as a linear function of the secondary current. In tests 5 and 6 (Figs. 9 and 10) Supply B was used. The chief impurity in these tertiary wave shapes is the third harmonic. This component was 19.2 per cent of the fundamental with the lighter load but only 6.5 per cent with the heavier load, the resulting change in the crest factor being from 1.593 to 1.509. The addition of load here reduced the crest factor. Figs. 11 and 12 (tests 7 and 8) are especially interesting in that they show great changes in wave shape and crest factor produced by simply changing the load. The chief impurity in the tertiary wave shape is again the third harmonic. Here an increase in the load lowered this component in value from 36 per cent to 24 per cent, and, what is of more importance, practically reversed its phase, resulting in a change in the crest factor from 1.438 to 1.714.

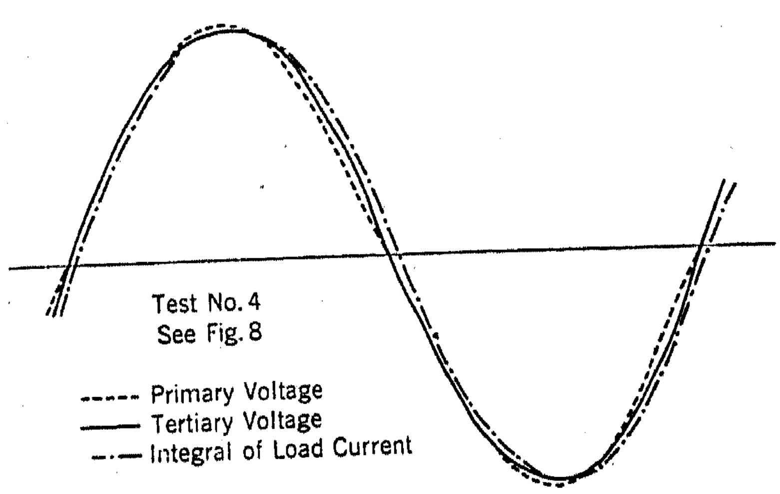


FIG. 13

The addition of load in this case therefore increased the crest factor.

There is some evidence that the tertiary voltage wave form is more likely to resemble the secondary voltage wave form than the wave form of the primary voltage. No attempt was made to determine the high-tension wave form directly, but in three of the tests this wave shape was derived by integrating the current through the condensive load expressed as a harmonic series. Dividing this integral by the capacitance of the load gave the harmonic series representing the secondary terminal voltage. Figs. 13, 14 and 15 compare the several voltage waves as mechanically synthesized from their respective harmonic series. The scale of these figures is so chosen that all the waves have the same r.m.s. value. The secondary wave shape determined in this manner is not strictly correct, on account of some corona current which was present. By inte-

grating the whole load current and thus ignoring the in-phase component due to corona the resulting wave is made to appear to the right of the true curve; and, further, since the shift of the fundamental is proportionately greater than for the higher harmonics, the shape of the wave is affected. This error is especially noticed in Fig. 14, where the capacitance of the load was the smallest and the corona current therefore largest as compared to the condenser current. Fig. 15 shows a marked difference between the primary voltage wave and the secondary voltage wave obtained by integration, but the latter wave is in fair agreement with the wave of tertiary voltage.

These tests, few as they are, show the necessity for a knowledge of the crest factor *under the particular conditions of the*

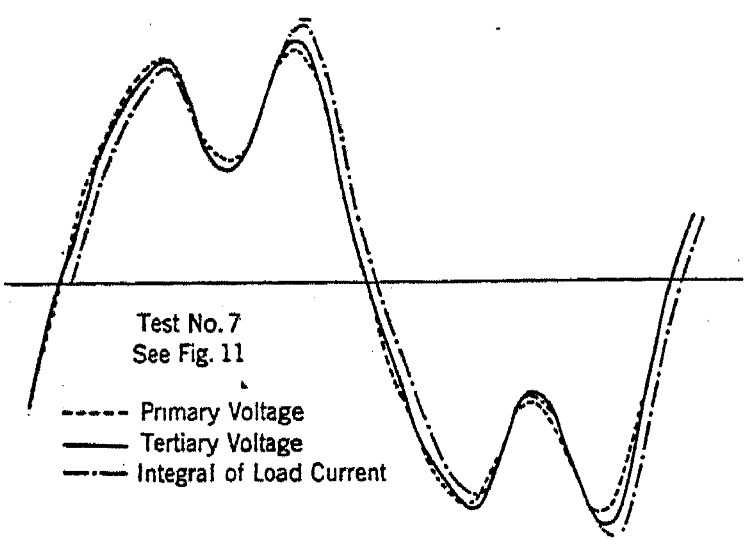


FIG. 14

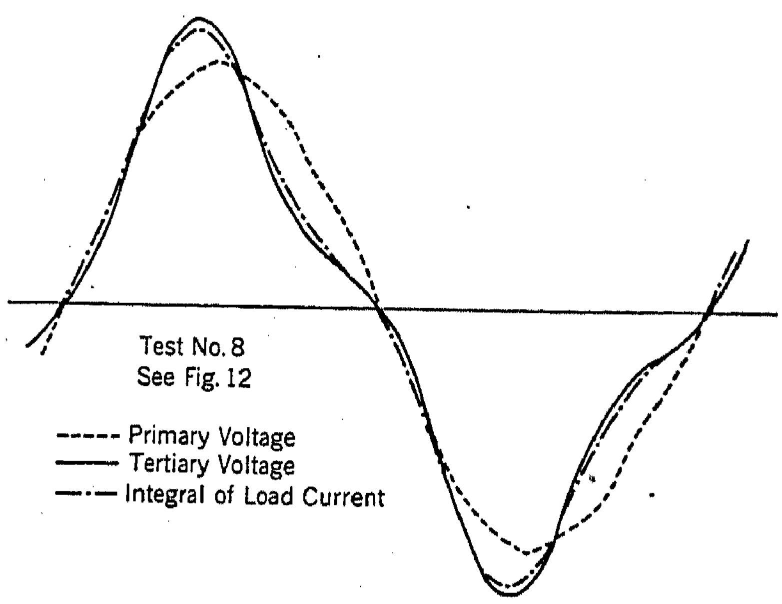


FIG. 15

test in order to use the voltage of a tertiary coil as an accurate measure of the secondary voltage.

SECONDARY VOLTAGE MEASURED BY CREST VOLTMETER

Crest voltmeters having indications dependent upon the average value of the charging current taken by a condenser and thereby measuring the peak value of the voltage across the condenser have been used in experimental testing.[4] In order to learn something of the usefulness of these meters under conditions prevailing in ordinary high-tension testing, a meter of this type was also used to measure the high-tension pressure in all but test 1.

4. Calibration of the Sphere Gap Voltmeter, Chubb and Fortescue. TRANS. A.I.E.E., 1913, Vol. XXXII, page 739.

The Electric Strength of Air, Whitehead and Gorton. TRANS. A.I.E.E., Vol. XXXIII, 1914, p. 951.

For clearness the observations are here exhibited in a separate table.

TABLE II—SECONDARY PRESSURE MEASURED BY CREST VOLTMETER AND EXPRESSED AS THE R.M.S. VALUE OF THE SINE WAVE OF EQUAL PEAK

Test	Supply	Crest voltmeter reading	Sec. volts by gap r. m. s.	Sec. volts by integ. load cur.	Error of crest voltmeter per cent
2	*A*	96,600	96,900		−0.3
3	*A*	69,600	69,300		+0.4
4	*A*	57,500	57,600	57,400	−0.2
5	*B*	96,400	96,600		−0.2
6	*B*	68,300	67,400		+1.3
7	*C*	82,700	57,900		+42.8
8	*C*	56,900	57,600	57,100	−1.2

The measurement of high voltages by this method has substantially the simplicity of the ordinary methods for low voltage, with a precision apparently limited only by the difficulties of original calibration, save in one respect. Meters of this type, employing rectifying bulbs, are inherently incapable of giving indications proportional to the highest peak of a voltage wave which has several peaks in a half-cycle. With waves of this kind the current through the condenser will have both positive and negative lobes in a half-cycle. Now the crest value of the voltage is proportional to the maximum quantity of electricity in the condenser, and this quantity is proportional to the net area of the current-time curve for one half-cycle, negative lobes counting as negative areas. The permanent magnet type instrument in series with a rectifying bulb indicates the average positive current throughout a whole cycle and thus measures the sum of the areas of all the positive lobes of the current-time curve in a whole cycle, failing to subtract the areas of the negative lobes when these are present in the first half-cycle and adding the areas of the same lobes when they appear on the positive side in the second half-cycle. The error is therefore a double one, both elements causing the meter to measure a current greater than the true average current and therefore to indicate a voltage greater than the true high-tension voltage. Test 7 (Fig. 11) shows a case in which an extreme effect of this kind was purposely obtained by resorting to the use of Supply C. Distortions of this degree are difficult to produce and are not likely to occur in practise.

An error of another kind will be introduced in the measurement unless the frequency of the e.m.f. being measured is the same as the frequency employed in the original calibration of the meter. Since with a constant e.m.f. the meter reading will vary directly as the frequency, the proper correction can be easily applied.

TABLE III—SECONDARY VOLTAGE DERIVED FROM PRIMARY VOLTAGE

(The secondary pressure expressed as the r. m. s. value of the sine wave of equal peak is assumed equal to r. m. s. value of primary pressure multiplied by the ratio of its crest factor to $\sqrt{2}$ and by the ratio of turns.)

Test	1	2	3	4	5	6	7	8
Supply	*A*	*A*	*A*	*A*	*B*	*B*	*C*	*C*
Sec. currents (amps.)	0.024	0.035	0.114	0.342	0.031	0.110	0.0306	0.323
Primary r. m. s. volts = E_1	238.4	228.5	160.0	247.9	205.4	146.6	265.7	198.5
Pri. voltage crest factor ÷ $\sqrt{2}$ = F_1	1.005	1.014	1.007	1.000	1.118	1.042	0.989	1.016
Ratio of turns = K	417	417	417	208	417	417	208	208
Calculated sec. volts = $E_1 F_1 K$	99,900	96,600	68,700	51,700	95,700	63,700	54,700	42,000
Sec. volts by gap, r. m. s.	103700	96,900	69,300	57,600	96,600	67,400	57,900	57,600
Per cent error	−3.7	−0.3	−0.9	−10.2	−0.9	−5.5	−5.5	−27.1
Figures	5	6	7	8, 13	9	10	11, 14	12, 15

As would be expected, the primary voltage, even when corrected for crest factor, is not, in general, a satisfactory measure of the secondary voltage, largely because the wave form of the primary voltage may or may not resemble the wave form of the secondary voltage under given circuit conditions, the difference being especially noticeable in Fig. 15. Of course the use of the simple ratio of turns is responsible for part of the error, because the internal resistance and reactance drops in the transformer are thereby neglected.

Conclusions

For the conditions of test and with the apparatus used, the following conclusions may be drawn:

It is possible to wind in a high-tension transformer a tertiary (or voltmeter) coil in such a manner that the voltage induced in this tertiary coil, when corrected for crest factor, is a satisfactory measure of the secondary terminal pressure.

A crest voltmeter provides a convenient and, in general, an accurate means for measuring high voltages, though errors can be introduced by the use of extremely distorted voltage waves.

The primary voltage, even when corrected for crest factor, is an uncertain measure of the secondary voltage because the respective wave forms may differ.

DISCUSSION ON "CREST VOLTMETERS" (SHARP AND DOYLE), "THE CREST VOLTMETER" (CHUBB), "THE VOLTMETER COIL IN TESTING TRANSFORMERS" (HENDRICKS), "NOTES ON THE MEASUREMENT OF HIGH VOLTAGE" (WORK), NEW YORK, FEB. 8, 1916.

E. E. F. Creighton: The question of the measurement of high frequency is always important, and always will be important until all the problems relative to the protection of apparatus are solved. Dr. Sharp's statement that the kenotron might be used for the measurement of high frequency is of the greatest importance. The dielectric spark lag of a perfect vacuum is practically infinite, because there are no ions present. Going down to a vacuum of something like fifteen millimeters in the usual gases the dielectric spark lag decreases to about the low value at atmospheric pressure.

It would be of interest to know in these cases how high frequencies were used in the kenotron. I had a feeling that there was not sufficient ionization in the tube to reduce the dielectric spark lag to a value which might give direct indication of the voltage. If the dielectric spark lag is not great, or if it can be taken care of at high enough ionization with the filament, there should result another instrument for measuring transitory waves in transmission lines. These waves are very difficult to get at.

At the present time we have to depend upon a number of sphere gaps connected in parallel, each one set to a different voltage. For example, in the measurement of a 13,000-volt circuit we naturally begin with the sphere gap set on double potential. and go on from that to 2.5, 3, 3.5, 4, etc. In series with each one of these sphere gaps is placed a recording device, usually operating on the principle of the Branly coherer. If, however, the kenotron can be used for these high frequencies, and high potentials, it will give a simpler method of measuring and recording these transitory voltages.

F. W. Peek, Jr.: I have used one or the other of these methods in measuring high voltages at the ordinary frequencies of power transmission, high-voltage direct current, transient voltages of the duration in some cases, of a few millionths of a second, and continuous high-frequency voltages. The voltage range in these measurements was from zero to almost a million volts. I shall review the various methods and state their possibilities and limitations as I have found them in my experience.

For the purpose of discussion, the methods of measuring high voltages may be divided into three classes, (1) the spark gap; (2) the crest voltmeter consisting of a condenser and a rectifier in combination with frequency meters, ammeters, or static voltmeters connected directly to the high-voltage line; (3) the voltmeter coil, on the high-voltage side of the transformer, in combination with a low-voltage crest voltmeter.

In discussing (1), the spark gap, it is only necessary to consider the sphere. With this form of gap there is no humidity correction to make. The correction for air density is readily made. The sphere gap will measure correctly the crest voltage of the most distorted wave; it will measure correctly, direct current, high frequency over a considerable range, and impulse and transient voltages of a few micro-seconds duration.[1] In many high-voltage measurements the sphere gap is very desirable, in fact, necessary, to detect oscillations. It is invaluable in the laboratory in investigating transient voltages. The disadvantage of the sphere gap is that it must be set.

Under (2), two forms of crest voltmeters connected directly to the line have been described. In the method described by Mr. Chubb unidirectional voltage is applied to a condenser by means of a rectifier. The current and frequency are read. Good results may be obtained if the wave shape is not much distorted. Errors will result if there is insulation or corona loss in the condenser as this loss current will be read on the meter. If the voltage wave has a double peak, or a sharp peak, large errors will result. This is shown in the paper by Mr. Work where a wave of the type Fig. 14 causes an error of over 40 per cent. This is a much larger error than would have resulted if no attempt had been made at correction. In the method described by Messrs. Sharp and Doyle the rectified voltage wave is applied to a condenser. The condenser is thus charged up to the maximum of the wave. The condenser voltage is read by a static voltmeter. I have used this method directly on the line for voltages of over 100 kv. I believe it to be the more practicable of these two methods. Good results may be obtained if the insulation is very good and the condenser is of fairly high capacity. If leakage occurs the voltage reading will be too low. Thus, for high voltages, the condensers become excessively large. More will be said of the application of this method at low voltages, later. Both of these methods have extensive use in the laboratory and may be of use in some practical work. Neither will measure transients or detect oscillations.

The voltmeter coil, method (3), consists of taps brought out from a few turns of the high-voltage winding of the transformer, generally at the neutral point where the voltage above ground is zero. I have for years used a transformer, designed by Mr. Hendricks, equipped with such a coil. I have made hundreds of check tests with voltmeter coils and find that when the transformer is properly designed, and the coil properly placed, the voltage and the wave measured from the coil check very closely with the voltage and wave shape across the high-side winding. The voltmeter coil requires practically no extra equipment and involves practically no extra cost. The effective voltage may be read by a standard voltmeter, the maximum may be read by a

1. F. W. Peek, Jr., "The Effect of Transient Voltages on Dielectrics." TRANS. A. I. E. E., Vol. XXXIV, 1915, p. 1857.

low-voltage crest voltmeter. This crest voltmeter may be of the type described by Messrs. Sharp and Doyle and need not be large and expensive as in the case of the high-voltage types. An oscillogram of the voltage wave may be taken at any time. The voltmeter coil with crest voltmeter seems to be decidedly the best and most convenient method of measuring high voltages in practical testing where continuous readings are desired. This should always be supplemented by a sphere gap set slightly above the applied voltage to detect oscillations, etc.

The methods of measuring high voltages may be summarized as follows:

(1) The sphere gap will measure correctly practically any form of voltage. It is the only method, at present, of measuring certain high-frequency and transient voltages. It is invaluable in the laboratory and in much commercial work, especially where transients are likely to occur.

Its disadvantage is that it does not read continuously. This is not always a disadvantage as the transformer may be calibrated.

(2) The various crest voltmeters consisting of condensers, rectifiers, voltmeters, ammeters, and frequency meters, connected directly to the high side of the line are useful over a limited range in practical work, but become troublesome, liable to error, and expensive at high voltage. They are not always accurate with distorted waves.

(3) The voltmeter coil in connection with a low-voltage crest voltmeter involves practically no extra space or expense and gives good results. The voltmeter coil with crest voltmeter and supplemented by a sphere gap to detect oscillations offers the best arrangement for general commercial testing.

F. M. Farmer: The problem of measuring high voltages usually involves two things, the mean effective value and the maximum value.

The first method used for measuring high voltages employs the low-tension voltage and the ratio of transformation. This method is deficient, in that we do not know anything about the ratio under varying load conditions nor have we any knowledge of the crest factor.

The next scheme developed was the use of electrostatic voltmeters on the high-voltage circuit. That gets rid of the ratio difficulties and gives us a mean effective value, but the scheme has voltage limitations because of construction difficulties at very high voltage and also because stray electrostatic field troubles become serious. Furthermore it does not give the crest voltage.

The test coil seems to be the proper thing for measuring mean effective values on the high-voltage side, but there again, some investigation is necessary to be sure of the ratio of the test-coil voltage to the total voltage under various load conditions and various dispositions of the sections of the secondary winding. Of course, in our very high-voltage testing, it is not customary to

divide the high-tension winding, but in the ordinary testing transformer for routine testing at moderate voltages, the secondary winding is split up into two, four, or even eight sections, so as to be able to get the maximum kilovolt-ampere capacity of the transformer at all voltages.

The best arrangement, therefore, seems to be the use of a test coil in the high-tension winding of the transformer. An ordinary voltmeter gives the mean effective value and a crest voltmeter gives us the maximum value.

There is one question I would like to ask Mr. Chubb. Is there any variation in the capacitance of the condenser bushing? At the very high voltages is it possible that that capacity will change and thus introduce an error. In other words, does the capacity remain constant at all voltages?

Frederick Bedell: One feature of the crest voltmeters described in these papers is that it is possible by means of them to obtain an instrument reading of crest voltage without the use of a synchronous contactor. Another method for obtaining such readings without the use of any synchronous device is the method described[2] by Professor Ryan in which an impulse transformer is employed, in place of a synchronous contactor, in conjunction with the Duncan method for obtaining a-c. wave form. The impulse-transformer method makes unnecessary the synchronous contactor, but it does require the locating of the maximum reading by trial, so that readings of crest voltage are not made directly as by the crest voltmeters we have just heard described.

Comfort A. Adams: I agree thoroughly with Mr. Hendricks that it is unnecessary to go to great lengths in the measurement of peak voltage, provided you have a suitable alternator and transformer and can depend upon the voltage wave shape impressed upon the transformer, in which case an ordinary voltmeter connected to a suitably placed voltmeter coil in the transformer, will give fairly accurate results. Moreover, such an equipment is desirable not only because it facilitates voltage measurement, but also because harmonics in the e. m. f. wave are undesirable on at least two other accounts. They produce undue heating of the dielectric in some cases, and also tend to encourage transients of still higher frequencies.

We have much to learn on this subject of insulation and cable testing. In high-voltage testing very high-frequency transients of excess voltage do occur, of this there is ample evidence, and until they are under control or brought within the realm of measurement, it behooves us to go slowly. As yet the spark gap in some form is the only simple detector of transients, but even if it could be conveniently arranged for measurement rather than for detection, it would still be dangerous because of its habit of producing the very kind of a disturbance it is employed to detect. Some materials withstand abnormal transients without rupture, provided they are not repeated too often, while

2. TRANSACTIONS, Vol. XVI, p. 345, 1899.

more fluid materials will fail and heal up many times before final rupture.

W. I. Middleton: It is very apparent from the papers that have been presented here today that the importance of a knowledge of the maximum voltage in connection with high-voltage testing is being appreciated more and more. It is not so much a question of whether the wave is distorted or not, but as to how much, and until generators giving a sine wave under a testing load are more commonly used than at present, it should be the desire of all interested to develop an instrument or instruments, that will give a direct reading in volts of the pressure at the peak, or crest, of the voltage wave.

In the early part of 1900 all of our investigations in high-voltage testing were done with the spark gap, and by its constant use under every condition of test that would arise, we were convinced that it was impossible to tell accurately what was the maximum voltage being applied to a cable under test.

In the latter part of 1911, while investigating the variations in the voltage waves of our testing set with an oscillograph, Mr. Dawes and I decided that as it was the peak of the wave we were interested in rather than its shape, an instrument much simpler than the oscillograph could be made, and in April, 1912, a working model of our instrument was being used in our factory.

The authors show some badly distorted waves obtained under testing conditions: We have experienced considerable difficulty from just such waves.

Fig. 1 shows a voltage wave obtained from a single-phase generator when it was supplying power to a step-up transformer, to the secondary of which was connected a cable undergoing test. The voltage wave is not unlike some of those shown in the papers. The current wave crosses the zero axis three times in a half cycle; its third harmonic has a greater amplitude than its fundamental. We have found the peak voltmeter very useful in checking such waves.

The instrument which we are using is based on the oscillograph principle, and therefore takes a very appreciable current, so we cannot use a condenser train as a multiplier without going to considerable trouble and expense. Therefore, we are obliged to use an instrument transformer to step down the voltage.

There has been raised some question regarding wave distortion taking place through a potential transformer. We have checked peak factors at various times with our peak voltmeter, but have never been able to detect any difference between those on the primary of the step-up transformer and those at the secondary of the potential transformer. As further, evidence, we have taken oscillograms of such waves.

In Fig. 2, the wave marked *G E* is the voltage wave of a special sine-wave alternator. As we have never been able to apply a load that would produce any appreciable change in the shape of this wave, we introduced an air-core choke-coil into the line in

series with the primary of the step-up transformer. Due to the non-sinusoidal drop through this choke-coil, the voltage at the transformer terminals had the form shown by the Wave T_1. The wave T_2 was taken simultaneously on the secondary of the potential transformer. The oscillograph vibrators were connected so that both waves were on the same side of the zero axis, and the multipliers were so adjusted that each voltage wave had the same amplitude. It will be seen that there is no appreciable difference in the shape of the two waves. There is, of course, a slight shifting of phase through the two transformers. Any variation of the voltage wave form is due to the fact that the current produces IR and IX drops in the transformer windings, which differ considerably in wave form from that of the applied potential wave. Also these waves were taken at only 13,000 volts. I realize that, at the higher voltages, distortion may occur due to capacity effects in the transformer windings.

If Dr. Sharp has developed an instrument that will trap and hold transient voltage peaks so that their value may be determined, I am sure that it will be found very useful in connection with high-voltage testing, especially in cable testing, where there is a large amount of capacity in the circuit. We have evidence that surges occur very frequently when the cable is long and the voltage is high. I am certain that many cables have punctured at voltages much higher than have been shown on the indicating instruments, due to surges occurring in the circuit. The presence of these transient peaks may be wholly unknown to the person making the test, unless he has some such instrument as Dr. Sharp describes.

J. R. Craighead: I made a few experiments and got some data in connection with the use of the kenotron with the electrostatic voltmeter on high-tension circuits at 60 cycles. In order to get the matter down to a point where a comparison could be made with the oscillograph with series resistance, voltages were used, not of the order being talked about this afternoon, but with the maximum limited to 7000 volts. The oscillograph was used photographically each time, and measurements made as carefully as possible in order to determine the correspondence between the electrostatic and the oscillograph. The electrostatic itself was calibrated on a sine wave after each successive trial, in order to be sure that the instrument itself did not change. Three waves were used, the crest factors varying from 1.405, which was practically a sine wave, up to 1.56. One of the three waves, the one whose crest factor was 1.56 had three peaks between each pair of zeros, although two of the peaks were very small.

The results, of which I have made a tabulation, show that the maximum difference within six successive trials taken of the three waves, between the crest voltmeter and the oscillograph, was about 0.2 of 1 per cent. The maximum difference on any trial was about 1.2 per cent, which was practically as close as a standard electrostatic voltmeter of 10,000 volts could be used

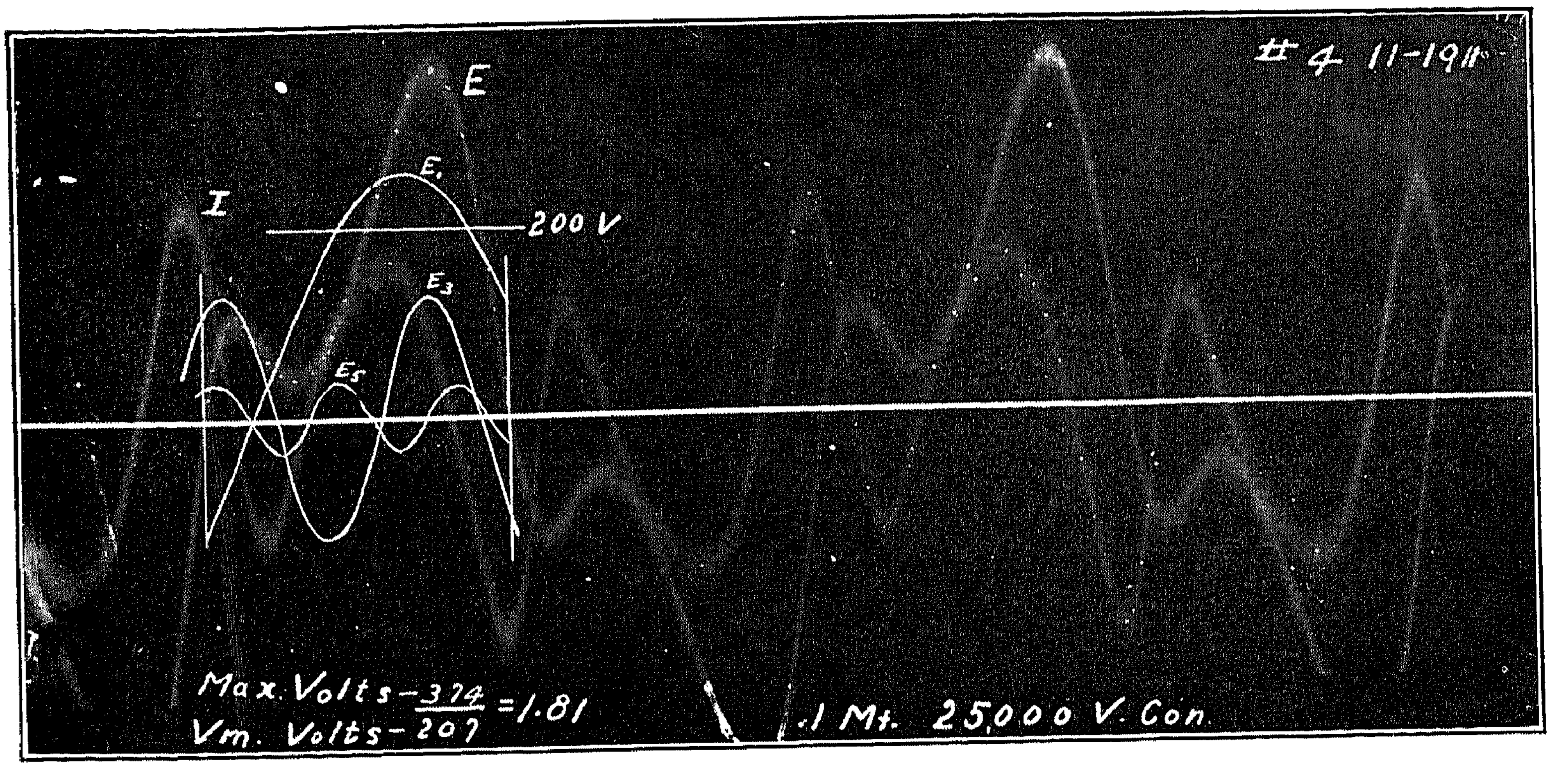


FIG. 1 [MIDDLETON]

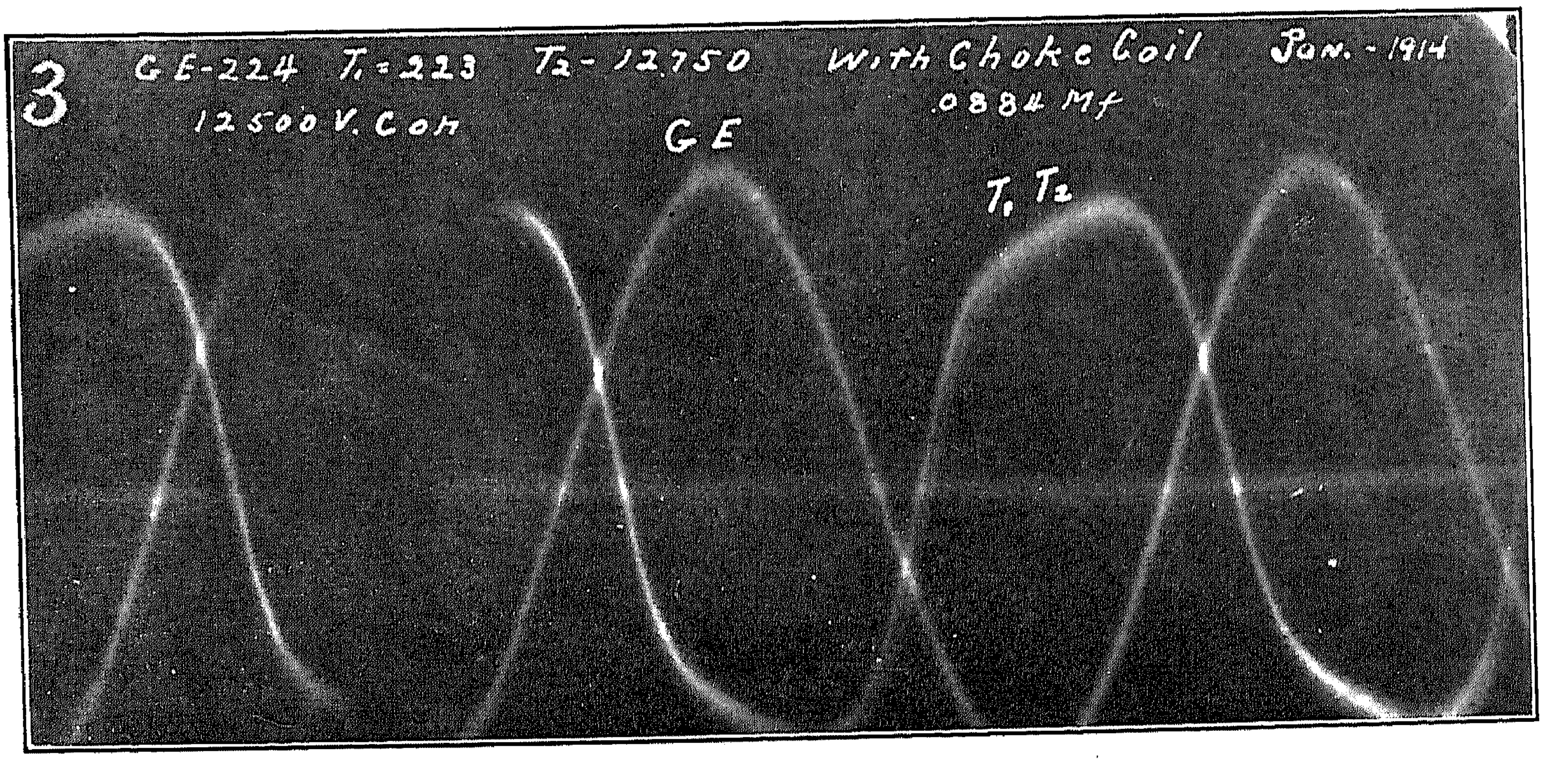


FIG. 2 [MIDDLETON]

at that point. All of the trials came within considerably less than 1.2 per cent, which represented the outside of the six.

In respect to the rectifier that was used, there is a characteristic of most rectifiers that causes them to have a rather definite voltage drop which is not altogether dependent on the current nor proportional to the current. In order to show as much of this drop as possible a kenotron was used which was capable of standing about 70,000 volts maximum, at about 10 per cent of the voltage it was expected to stand.

In respect to the capacity which was necessary in order to keep the voltmeter at a correct maximum reading, a very much smaller value than Dr. Sharp has suggested was found quite satisfactory. For the most part, these tests were made with 0.002 of a microfarad in multiple with the voltmeter itself.

The table to which I refer is as follows:

No. of test	Average crest factor	Average of maximum readings		Per cent variation of electrostatic voltmeter with Kenotron from oscillograph		
		Oscillograph through resistance	El. voltmeter with kenotron	Maximum positive	Maximum negative	Average
1–2	1.405	7186	7175	+ 0.7	− 1.0	− 0.2
3–4	1.485	7126	7185	+ 1.2	....	+ 0.8
5–6	1.56	7165	7165	+ 0.5	− 0.4	0

I ask Dr. Sharp if his tests were all made, as shown on the diagram, on ungrounded circuits or whether he used grounded circuits in any instance, and at what voltages the tests were made.

C. L. Dawes: There is still another type of crest voltmeter which has not been mentioned. We have found the oscillograph type of crest voltmeter very useful in connection with cable testing, but there are certain conditions under which it cannot be used to advantage because of the very appreciable current which it requires for its operation. This has led me to develop an electrostatic type of meter. The principle of the instrument is not original, but was suggested to Prof. A. A. Laws and myself by a paper written by E. T. Jones, appearing in the *Philosophical Magazine*[3] some time ago. However, the instrument there described was wholly unsuited for high-voltage testing, and therefore it was necessary to modify the design very materially.

Fig. 3 shows the general scheme of the voltmeter. For the sake of clearness, no attempt has been made to show the parts in their correct proportion. A phosphor-bronze filament is

[3] "A Short Period Electrometer and Its Use in Determining the Frequencies of Slow Electrical Oscillations." *Philosophical Magazine*, 1907, p. 238.

stretched between two points of support AA, the proper tension being secured by the spring B. This filament is held to the spring by a short length of silk thread for insulating reasons. Beside and close to this filament a small silk thread C is stretched, being drawn as tightly as its tensile strength will permit. Across the filament and thread, midway between the supports A, a small mirror D is cemented.

In front of the filament and very close to it, a brass plate E is fastened. Through the center of E, there is a small hole just large enough to allow a beam of light to enter and leave. The filament and this plate are connected together to form one terminal of the instrument. The other terminal of the instrument is the small brass plate F, secured to the hard rubber barrier.

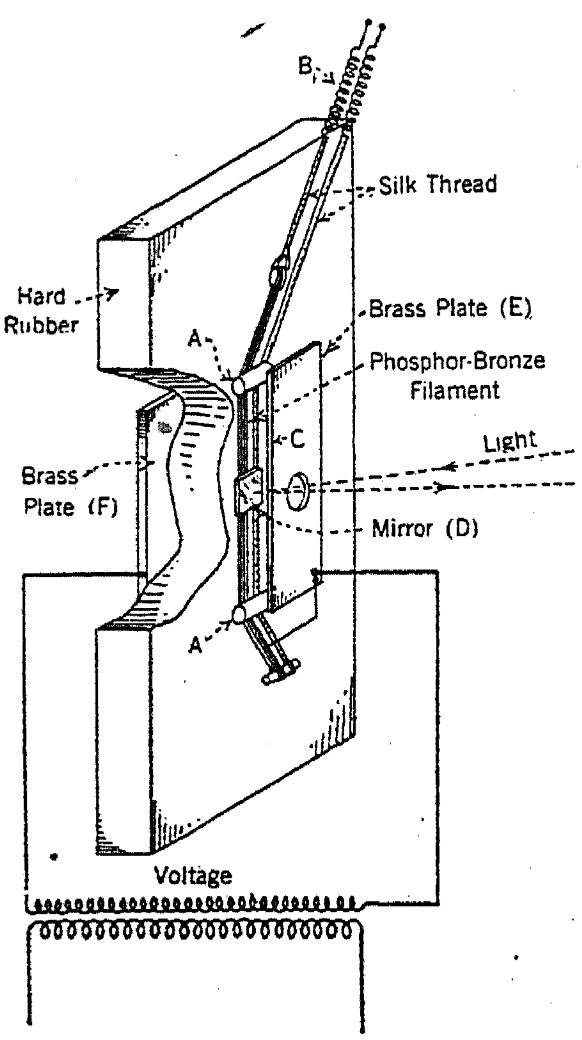
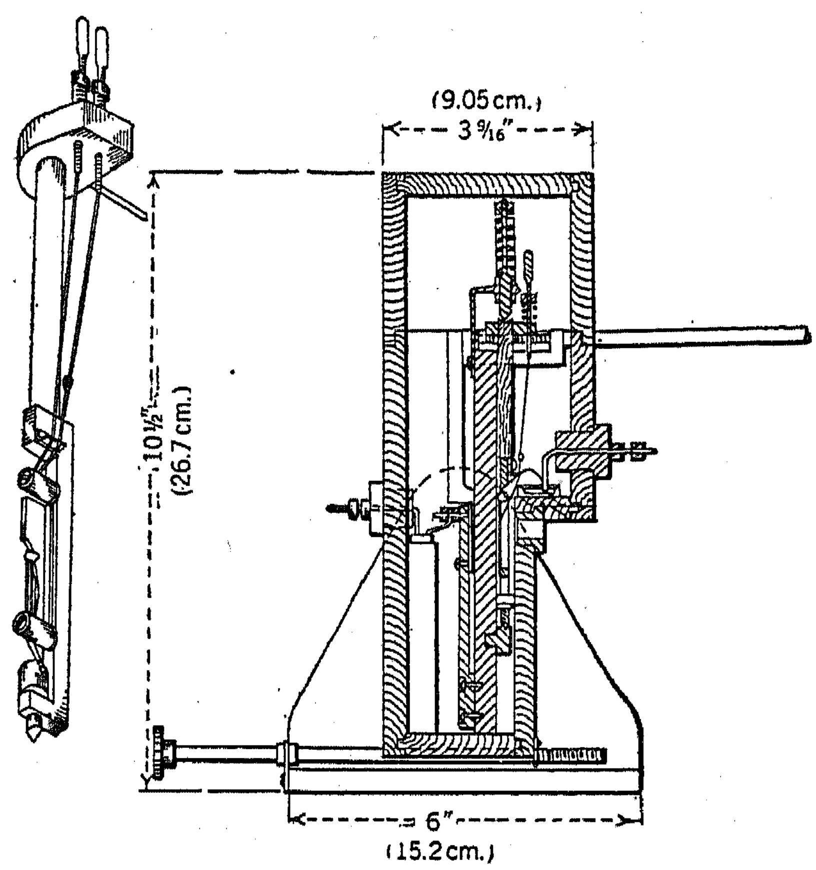


FIG. 3



FIGS. 4 AND 5

This barrier acts as a dielectric to prevent breakdown between the terminals.

When the brass plate E and the filament are both positive, there is electrostatic repulsion between them because like charges exist on both. On the other hand, there is attraction between the plate F, which now has a negative charge, and the filament. As the silk thread is not influenced by the electrostatic charges, it remains practically stationary, serving only as a hinge about which the mirror swings. Therefore, the left hand side of the mirror will be drawn toward the barrier. When the polarity is reversed, the mirror will still deflect the same way, because the charges on plate E and the filament are always the same and those on plate F and the filament are always opposite. Therefore, the mirror deflections are proportional to the square of the voltage and the deflection is always in the same direction. The

deflection of the mirror is read by noting the breadth of a band of light upon a scale. Fig. 4 shows the vibrator which is removable from the barrier.

The instrument does not operate satisfactorily in air, due to corona and brush discharge from the filament, therefore it is necessary to immerse it in oil. Fig. 5 shows a cross-section of the instrument immersed in a box containing white oil. Connections to the plate are made through mercury cups, which connect to binding posts through hard rubber bushings.

It will be appreciated that this instrument has so little electrostatic capacity that it is almost negligible. Therefore, it is very easy to use it in connection with a condenser-train multiplier having a very small capacity. Also the instrument may be used to measure induced potentials upon insulated bodies whose capacity to the system is so small that the voltage would be disturbed by even the small capacity of other types of electrostatic instruments. For instance, Mr. Middleton and I have frequently used the instrument to measure induced charges on cable sheaths and on insulated conductors having high-potential wires in their neighborhood. This instrument does not need to be grounded, but may operate at potentials far above that of the ground. For instance, we have used it to measure a potential of 30,000 volts when one terminal was at 30,000 volts and the other at 60,000 volts above ground potential. Up to the present we have calibrated the instrument by connecting it to the secondary of a step-up transformer which is delivering no load. Under these conditions, we know the voltage wave to be essentially sinusoidal. The instrument at present can be used safely up to 30,000 volts, but there is no apparent reason why it cannot be designed to operate at much higher potentials than this, provided that appreciable corona discharge from the filament to the oil is not allowed to occur.

This voltmeter is independent of wave form and negative loops; although it cannot register surges, it has been able to indicate the apparent peak of surges in the circuit to which it was connected.

John B. Whitehead: All three of these papers describe the use of the electric valve for measuring the maximum value of voltage. Reference is made to the work of Dr. Gordon and myself in which we measured corona voltages at frequencies higher than sixty cycles. We used the mercury electric valve for obtaining maximum values of voltage at the higher frequencies, in much the same way as now described in these papers.

I mention this in order to answer Mr. Creighton's question as to the frequency at which the valves may be used. At that time we were working up to 3000 cycles. From the nature of the kenotron, I see no reason why it should not be available for far higher frequencies than this.

I wish to describe some experiments we have been making with still another type of crest voltmeter, namely, the corona voltmeter.

It has been frequently brought to the attention of the Institute that the value of the voltage at which the corona comes out on clean wires is extremely sharply marked. Suitable corrections, which are now perfectly well understood for temperature and pressure, may be made. It is quite possible to read and re-read corona voltages on clean wires to a far higher degree of accuracy than the constancy of the usual circuit, even in a laboratory, where precautions to secure constancy are taken.

Within the last two years I have been trying to use the principle of the breaking out of corona on the peak of the voltage wave as a basis for direct observation of crest voltages. The great difficulty in using the corona, a difficulty which is at once obvious, is that it is directly dependent upon the size of the wire, and that consequently for any range of scale in such an instrument the size of the wire would have to be changed. There is another difficulty, namely, that some method of detecting the beginning of corona, other than by direct visual observation must be devised.

I have met the first difficulty very satisfactorily, so far, by enclosing the whole corona tube, with its central wire, in a larger outside tube, varying the pressure in this outer tube and, reading the pressure and the temperature in order to apply the correction. The instrument can then be set for any voltage by varying the pressure in the outer containing cylinder, or, if it is desired to measure an unknown voltage, it is simply a matter of lowering the pressure until corona appears. In other words the range of the instrument will be taken care of by running the pressure either up or down in the outer containing tube.

For the observation of the beginning or presence of corona, we have developed three very satisfactory methods. The first is that which uses the gold-leaf electroscope in connection with a small electrode outside of the cylinder forming one side of the voltage terminal, as described in my papers, the *Electric Strength of Air*. This electrode is placed directly opposite a few small holes in this cylinder and the ionization that comes from these holes is quite sufficient to discharge even a crude and rugged type of electroscope.

The second method is by the use of the galvanometer in connection with d-c. voltage. In order to use this method, the electrode is increased in size, so as to form still a third outside cylinder very close to the main cylinder forming one side of the high-voltage circuit, the latter cylinder being perforated with many holes over its whole circumference so as to provide a very large aggregate opening for ionization. With d-c. voltage on the enlarged electrode and a galvanometer in series, the beginning of corona is marked by a sudden deflection.

Still a third method which has been surprisingly satisfactory is the use of the telephone. We enclose a telephone transmitter inside of the pressure cylinder. We do not normally think of a frequency of 60 cycles as one which would give any appreciable

note with a telephone transmitter. There is, however, something other than the normal 60-cycle note in the high voltage corona and it is these higher spark tones which the telephone seems to pick out. The beginning of corona is attended by a sharp sound in a receiver connected to the transmitter located as described. We are now using all three of these methods of observation and they show a most gratifying agreement.

We can add a fourth method, if we will, the visual corona, always a very satisfactory means of observing the maximum point, but not suitable for an instrument for use in the open, as in a manufacturing shop, or power station. The eyes must be rested in the dark at least five or ten minutes before visual corona can be observed satisfactorily.

L. W. Chubb: In the paper by Sharp and Doyle the authors speak of leakage demanding a certain amount of capacitance in parallel to the meter. The dielectric resistance of electrostatic voltmeters is usually very much higher than any condenser, unless it be of the air type. Also, the rectifier resistance is higher in the reverse direction than that of the condenser, so that if more condensance is put in parallel we should expect more rapid discharge in spite of having more power stored.

Very likely the leakage between peaks is due to corona.

One of the speakers stated that he used less condensance when working at 7000 volts. Is it not likely that this was possible because the voltage was below the corona point and leakage was low.

Dr. Sharp speaks of registering the magnitude of surges with such an instrument, but I believe he will only reach a middle ground in obtaining a surge. The authors state in the paper that "if it does not build up on the first cycle it will on succeeding cycles." Sometimes the surges which come along are very steep, high frequency, and very quickly damped, so that if the first impulse is not enough to charge the electrostatic voltmeter and condenser, the following impulses will not be enough to raise the charge to the voltage of the first impulse.

The current through the condenser at the instant of a surge should be of the order of amperes instead of milliamperes. The kenotron current is limited by space charge and by temperature of the filament, so the condenser cannot be filled on the first impulse. Also with any appreciable damping constant, the succeeding peaks of the surge will not charge the condenser to the voltage of the first peak.

The multiplier method with two or more condensers in series with the electrostatic voltmeter in parallel with one unit would not divide the voltage by ratio during the surge transient, even if there were no current limitation of the kenotron, for if the voltmeter is to store a charge there must be an equal charge displaced in the opposite direction in the series condenser because a d-c. component of current cannot flow through the series condensers.

The ratio of series condensers has also been found to be wrong unless the several units are guarded by the principles which Mr. Fortescue presented before the Institute some time ago, and unless corona is prevented on any but the outside terminal of the end condenser.

The resistance multiplier is also open to the same objection and errors will result unless capacity to ground and between sections is eliminated by electrostatic shielding.

With the kenotron used on the high-tension side of the transformer as shown by the authors, it must be capable of standing twice the peak voltage, for on the reversed half cycle the charge of the condenser and the transformer voltage are in series adding. It therefore seems that the scheme, measuring crest voltage, would not be very simple on voltages above 100 or 200 kv.

I was very much interested in the test results given in Prof. Work's paper, and I may add I have seen very much worse distortions in testing waves which, I think, will give greater errors with a volt coil. We have tested out the voltage per turn through the secondary winding under various load conditions. In one case I remember the voltage in a secondary turn was reversed in a certain part of the leg from what it was in others. This means that if the volt coil is to be accurate it must be perfectly coupled with the secondary, or must be placed in the average position. The average position depends on the nature of the load, because there is a shift of leakage reactance between the two coils.

Our experience with the volt coil has not been very satisfactory due to improper placing and the resonance of upper harmonics between the load and the leakage reactance of the secondary. However, the results shown by Prof. Work indicate that the volt coil is quite reliable, when crest factor corrections are made.

Clayton H. Sharp: I evidently did not make it clear that these experiments were all made on low voltage, that is to say, the instrument itself, the electrostatic voltmeter, was graduated to read a maximum of 250 volts. So questions of huge condensers etc. do not apply to these experiments. The crest voltmeter as we worked it out was used on voltmeter coils, tertiary winding of the transformer, and one side of it was grounded, so that the whole thing was practically at earth potential.

There is no reason why it cannot be used on a condenser multiplier, and I do not quite see why the multiplier needs to be a whole string of condensers. It can be one high-voltage condenser, and in series with it another one of large capacity connected to earth. Thus one condenser takes the bulk of the voltage drop, and the other one, of larger capacity, takes a small portion of the voltage drop and the crest voltmeter is looped about that. Then the indications of the crest voltmeter will depend on the ratio of the two. While I cannot speak from actual experience, I do not see any reason why it should not work, and I do not see any reason why Mr. Chubb's condenser bushing could not be used as the high-voltage condenser.

With regard to the measurement of high-frequency surges, etc., what we have in our paper is simply offered as a suggestion, and is not backed up with any very positive statements, because we have not the data or the experience on which to rest them. In our paper we say: " In conclusion, it may be noted that the arrangement given offers possibilities in the matter of the study of surges." It may do it, or it may not do it. It looks to me as if, while it is rather improbable, that the full value of the first peak of the high-frequency surge would be given, at the same time the arrangement might be of a good deal of value, even if it did not give the whole thing. Undoubtedly, with a surge there would not be the same building up effect that there is with a steady alternating-current, because the first peak is the one that counts, the oscillations being damped out rapidly after that.

It will be noted, however, that if one kenotron has not a large enough saturation current to catch the surges perhaps two or three or more in parallel may have.

When commercial instruments are available by which the crest values of waves can be measured as readily as the effective values now are, we shall avoid a lot of trouble, escape a lot of mysterious things which occur in high-voltage testing and increase the accuracy and the worth of such work.

C. F. Harding: One very important feature of high-voltage measurement which has not been touched upon in the foregoing papers is the establishment of a more satisfactory primary standard than the combined needle and sphere spark gaps. That these are not entirely satisfactory is freely admitted, for they are subject to correction for barometric changes and in practise it is found very difficult to make the two standards coincide within the range between 30 kv. and 50 kv. where both are standard. Tests covering a large voltage range such as is required upon a line of pin type insulators or upon varying numbers of suspension units in a string are difficult to make when a double standard involving variable and uncontrollable factors is used.

Whereas the meters described in these papers are designed and intended for intermediate or secondary standard use and must be referred to the needle and sphere gaps for calibration, it may be of interest to reconsider the principle of the electrostatic field with a view toward its use as a high-voltage standard.

If, for example, a uniform electrostatic field can be maintained at the center of two horizontal circular metal plates of a relatively great diameter as compared with their distance apart, and if a small circular disc be cut from the center of the lower plate and supported upon a float just below the plane of the lower plate in a tank of liquid, the force required to raise this disc to the level of the lower plate can be readily calculated in terms of the voltage impressed between the plates. With the plates near together this voltage may be small and therefore accurately determined by other means than the spark gap. If

the field is maintained uniform by applying higher voltages between the plates as they are separated from one another, the force necessary to hold the movable disc in the plane of the lower plate will be constant and the voltage will be directly proportional to the distance between plates.

Such an electrostatic voltmeter has been constructed at Purdue University by Messrs. B. S. Wright and H. R. Holman under the direction of the writer, and readings at low voltages confirm the theoretical straight line relation between voltage and distance between plates. This line extended may be used within the limits in which no corona forms for a standard of voltage, the particular instrument constructed having a range of 180 kv.

It should be noted that such a meter would indicate effective volts and that the crest voltage would be determined only after the wave form was known. However, since the crest voltmeters are equally restricted in determining effective voltages and since the latter values at high potentials are becoming of more importance as the losses in dielectrics are being studied quite as much as break-down voltages, further steps are being made to perfect the details of this instrument with the hope that it may be seriously considered in the future as a standard for high-voltage measurement.

W. D. Peaslee: Referring to Fig. 1 of Mr. Chubb's paper it must be recognized that the arrangement as shown will give satisfactory indications only on steadily maintained voltage conditions, as the instrument intrinsically gives a deflection that is some function of the entire wave or series of waves and will indicate an entirely unknown function on a portion of a surge which lasts in terms of cycles rather than seconds. For this reason the indication of the instrument is a measure of maximum voltage only when it is calibrated and used on a particular wave form. What is needed is an instrument that will indicate the maximum voltage applied regardless of wave form and even when this maximum is a combination of a normal frequency (60-cycle) voltage and a superposed high-frequency wave or transient.

It has been shown[4] that the voltage stress imposed on a system by the combination of audio and radio-frequency voltages is substantially the sum of the individual stresses imposed by the individual voltages.

It is therefor necessary in high-voltage testing that an instrument be developed that will indicate at the moment of failure, the actual maximum stress on the medium under test whether consisting of a steady 60-cycle voltage, a transient or a combination of the two. The sphere gap, as has been shown by Prof. Ryan and Mr. Peek gives a fairly reliable measure of the stress resulting from any of these combinations but it is in difficulty of

4. Sustained Radio Frequency High-Voltage Discharges" by Harris J. Ryan and Roland G. Marx, *Proceedings of the Institute of Radio Engineers*, presented Sept. 16th, 1915 at San Francisco.

manipulation that this device fails in most cases rather than in a failure to give on break-down an accurate indication of the maximum stress, as intimated by the author.

The only device that seems at present to show distinct promise in this line is the cathode-ray cyclograph which, when properly handled will meet to a remarkable degree the requirements mentioned. The indications of this instrument are of maximum values and the calibration is easy. The duration of a surge measurable by it is dependent on the ability of the eye to catch the lengthening of the voltage line and it is hoped to develop a means whereby the eye may be replaced by an electric or chemical device and thus greatly shorten this interval.

As an indication of the extent to which this superposition of normal and high-frequency voltages may affect the results indicated by an instrument of the type described by the author we have found it possible, in the high-tension laboratory to subject an insulator to a stress just under flashover at 60 cycles and hold this stress on it indefinitely without puncturing the insulator. However, when besides this voltage at normal frequency we subject the insulator to a high-frequency stress consisting of several trains of damped high-frequency waves resulting from an arcing ground on the artificial line to which the insulator is connected it will be punctured with a very few applications, if the high-frequency stress is great enough. The instrument described in Mr. Chubb's paper will not give a reading that is a known function of the actual stress that punctured the insulator, but would indicate a lower maximum voltage than that under which the insulator actually failed.

Also the error mentioned in the discussion of Fig. 5 in the paper is a double one as the meter will not only integrate all the positive current areas and neglect the negative ones but will in the next half cycle, which should be entirely eliminated, integrate these negative areas. Thus the meter will read high by twice these negative areas. It will also be in serious error when applied to a wave consisting of a normal frequency wave with the superposition of high-frequency trains or surges.

Referring now to the paper by Messrs. Sharp and Doyle it is very probable that the charge will require several succeeding half waves. Also the fact that the instrument will not recede from it's maximum reading for an appreciable time after the application of the maximum, this time depending on the leakage of the equipment, may introduce serious errors in determinations made with this instrument. Suppose a test is required of 60,000 volts for one minute and that on bringing the voltage up the first few cycles, enough to complete the charge, this voltage was 60,000 but that it then dropped to 50,000 volts. The instrument, until leakage had permitted it to drop back to the lower voltage, would indicate that the required voltage was applied to the insulator while in reality it was subjected to 60,000 volts for a few cycles only and for the rest of the minute to only 50,000 volts. This might result in the acceptance of defective material.

This effect will be more serious the quicker the charge is built up and the less the leakage.

Also the use of the instrument as a surge trap is open to question until it is shown that the charge is built up in the time of the surge duration.

While these two papers are very valuable additions to the field of high-voltage testing and investigation, it would hardly seem that there was sufficient proof of the value and reliability of either method to accord them a place in the Standardization Rules at present, because of their inherent limits and also because it is quite probable that the cathode ray tube will be developed into a practical form for measuring these maximum values of voltage, both of normal frequency and transient wave trains, and of the two combined. As at present available it is much more satisfactory as a maximum-voltage measuring device than either of the instruments described and its failure on transients is due only to the inability of the eye to catch the record of the transient. If any change is made in the Standardization Rules the cathode ray tube should be carefully considered and given its rightful place as a means of measuring maximum-voltage values.

L. W. Chubb: Mr. Peek spoke of the errors due to corona. With the single condenser in series with the crest voltmeter there would be no error from corona, because you are measuring the voltage which is impressed upon the condenser. It does not matter how much corona there is, the line will supply all. If there are several condensers in series, the corona on and charging current of intermediate steps will cause an error except with the condenser terminal or with other similiarly guarded scheme. Each layer of the terminal is in its proper equal-potential surface, and there can be no corona, except possibly around the hat. These terminals will run to very high voltage without any corona at all, on the intermediate steps.

Mr. Peek spoke of the cost of such crest voltmeters going up as the voltage increases. I might add, with reference to the crest voltmeter described in my paper, that the cost goes down as the voltage increases. The condenser terminal is either a feature of the transformer, or it may be a roof bushing. As the voltage goes up, there is more current through the same condenser, and it takes less sensitive and cheaper instruments to measure it.

Mr. Farmer asked about the variation of capacitance of the condenser terminal. That is covered in the paper. It increased from 4 to 5 per cent from very low voltage up to 25 per cent over voltage, but this causes no error, as the crest voltmeter is calibrated in parallel with the spark gap and the variation is, taken care of in the calibration.

M. G. Newman: In the third paragraph of Mr. Hendrick's paper the statement is made: "For precise results at all loads and power factors, it is necessary and sufficient that the ratio of the flux linkages of the voltmeter coil and the high-voltage winding be a constant." This is done by the proper design and

placement of the voltmeter coil. I would like to explain the method of determining the accuracy with which the above condition is realized.

Referring to Fig. 6, transformer (*A*) is the transformer with voltmeter coil under test. Transformer (*B*) may be a potential transformer or any transformer which can be used to step-down to a secondary voltage which can be easily measured.

Voltmeter (1) is connected to the voltmeter coil of the transformer (*A*) and voltmeter (2) is connected to the secondary of transformer (*B*). Excitation is applied to the low voltage winding of the transformer (*A*). First a reading is taken at no load, voltmeter (1) and voltmeter (2) being read. Various loads are applied at (*C*) (either capacitance or inductance), the voltage and frequency being maintained constant and readings being taken on both voltmeters. The accuracy of the voltmeter coil is good if the ratio of the voltmeter (1) reading to voltmeter (2) reading remains constant from no load to full load.

We do not have to depend upon the accuracy of ratio of trans-

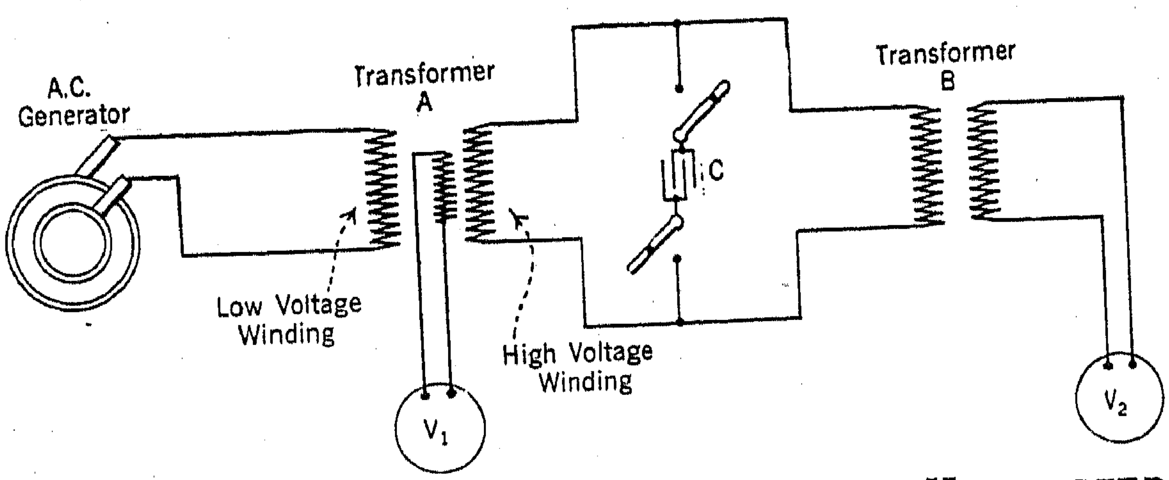


FIG. 6—METHOD OF TESTING THE ACCURACY OF VOLTMETER COIL

former (*B*). The assumption is that the ratio of this transformer will remain constant while tests are being made.

Errors due to flux leakage between the voltmeter coil and the high-voltage coil are shown to be very small.

A full capacitance load makes a small error in one direction and an inductance load an error in the other direction but with correct design these errors can be kept well below one per cent.

A. B. Hendricks, Jr.: I heartily agree with Mr. Peek in his final conclusion that "the voltmeter coil with crest voltmeter and supplemented by a sphere gap to detect oscillations offers the best arrangement for general commercial testing."

A crest voltmeter designed on the principle recommended by Sharp and Doyle, and connected to a voltmeter coil, has been constructed by Mr. Newman, and found to be in every way most satisfactory.

As it is built for low voltages and connected direct to the voltmeter coil, all parts are small, simple and inexpensive. In practise, the indications have been found to be correct and reliable.

Of course, this gives the crest value of periodic waves only, and does not indicate single transients of short duration.

As stated by Mr. Peek, the voltmeter coil reproduces the wave form in the high tension winding with such fidelity that there is no necessity for connecting static voltmeters or rectifiers directly in the high tension circuit, which is fortunate, since instruments designed for the extreme voltages contemplated have usually been unsatisfactory.

The method of using rectifiers, a condenser and a direct current voltmeter as described by Mr. Chubb is more complicated and less accurate on distorted waves of certain classes than the scheme described by Sharp and Doyle. It is not correct on multiple peaked waves, and the accuracy of the indications is absolutely dependent on the frequency. Neither of these objections applies to the scheme described by Sharp and Doyle, which is in other respects much simpler also.

Of course, every precaution should be taken in designing a transformer with a voltmeter coil to insure that the indications of the latter will be correct. Apparently, in the transformer referred to by Mr. Chubb, these precautions were not observed, with results as related by him.

As it seems to be difficult to convince the average engineer that the voltmeter coil is practically exact at all loads and power factors, I give herewith the results of tests recently made on a 300-kw., 300,000-volt transformer having one end of the high-tension winding permanently grounded. See Fig. 7.

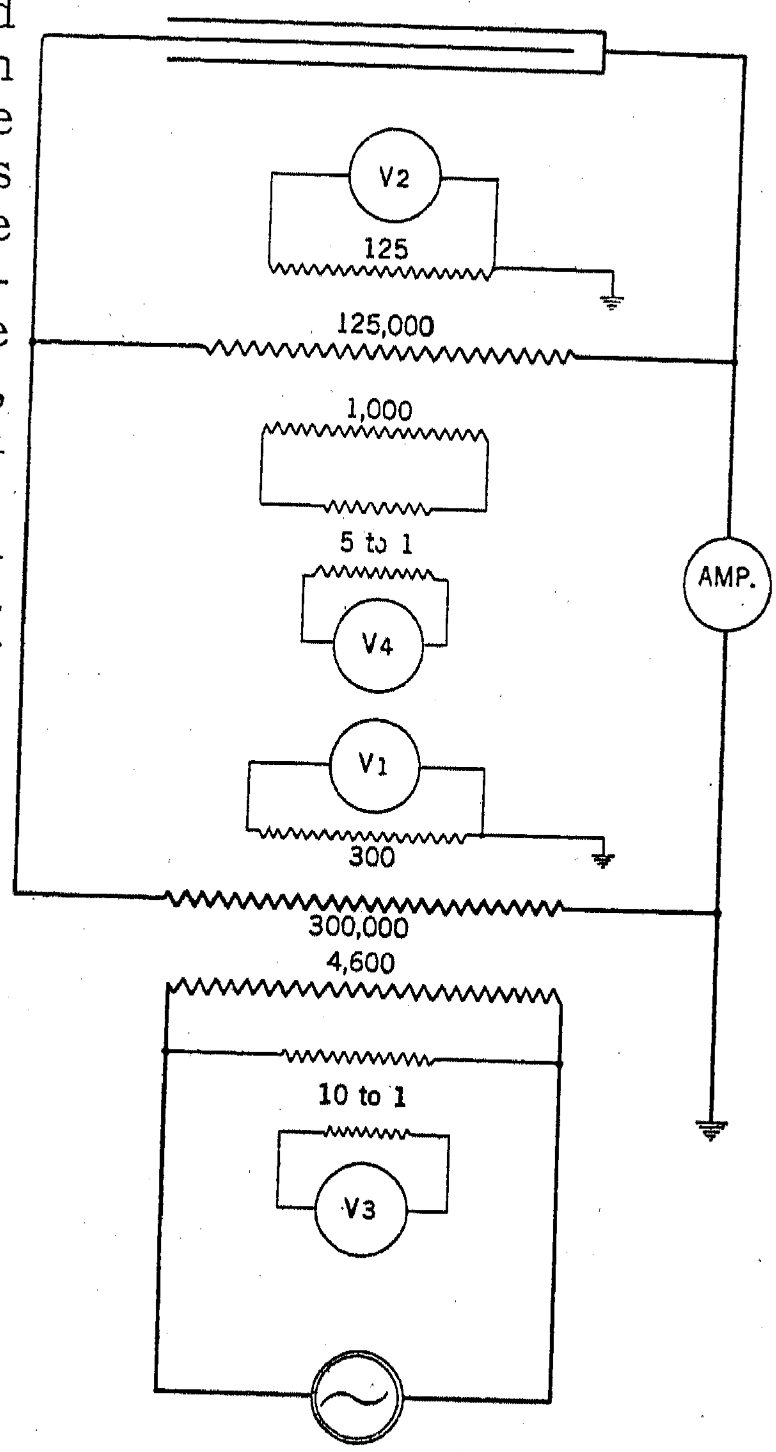


FIG. 7

The transformer was connected to a sine wave generator and the load consisted of a lead covered cable, especially made for use as a condenser.

The potential transformer consisted of another testing transformer rated 25 kw., 125,000 volts with one end of the high tension winding also permanently grounded.

With a pure condenser load it was found that the error of the voltmeter coil was too small to be detected by the best grade of portable dynamometer voltmeters, especially calibrated and interchanged, and read to 1/5 of 1 per cent.

This may be considered a zero error, since it is indeterminate by the most accurate form of commercial instrument, and even the sign of the error is unknown. At the same time the error,

reading from the low-tension winding through a potential transformer was 7.6 per cent or close to the measured reactance voltage of the transformer, as was expected.

Normal rating of testing transformer:

60 cycles, 300 kw., 300,000 to 4600 volts.

Voltmeter coil reads 300 at 300,000 volts.

Normal rating of main potential transformer:

60 cycles, 25 kw., 125,000 to 1000 volts.

Voltmeter coil reads 125 at 125,000 volts.

Ordinary potential transformers of 10 to 1 and 5 to 1 ratio were used on the low voltage side of the 300,000-volt and 125,000-volt transformers.

Test was made at 60,000 volts and 0.88 amps. in the high-tension circuit, the normal rating being 300,000 volts, 1 ampere.

The *absolute* variation of high-tension voltage from the winding ratio depends entirely on the magnitude and phase of the current and the *per cent* variation at 60,000 volts is of course five times normal.

The exciting current of the 125,000-volt transformer at 60,000 volts is so small that its effect on the power factor of the load can be neglected.

V_1 = actual reading on voltmeter coil of 300,000-volt transformer.

V_2 = actual reading on voltmeter coil of 125,000-volt transformer.

V_3 = actual reading on low voltage side of 300,000-volt transformer through 10 to 1 potential transformer.

V_4 = actual reading on low voltage side of 125,000-volt transformer through 5 to 1 potential transformer.

Amperes = actual reading on ammeter in 300,000-volt circuit
= condenser + step down transformer currents.

The normal rated voltage of each winding is given on the diagram of connections.

The readings given are from the actual indications of each instrument after correction in accordance with the special calibration of each.

After taking one set of readings, the voltmeters were interchanged as indicated, and a second set taken.

Normal voltage	300	125	4600	1000
	V_1	V_2	V_3	V_4
Reading at 0.882 amps.	60	59.9	57.16	96.3
	V_1 & V_2 interchanged		V_3 & V_4 interchanged.	
Reading at 0.879 amp.	60	60	57.16	96.3

These readings were repeated and checked many times, with no appreciable difference in results. All taps on the voltmeter coil gave similar results.

One volt corresponds to two divisions on scale, one-tenth

division being the extreme limit of observation, and probably beyond the accuracy of the instrument, or observer.

The voltages from transformation ratios of low voltage windings and potential transformer are as follows:

V_3 = 37,300 volts
V_4 = 60,200 "

The high voltage as determined by all the readings is therefore:

V_1..........60,000
V_2..........59,900—60,000
V_3..........37,300
V_4..........60,200

Voltage was fairly steady, but as each observer had to read two instruments, the observations are hardly reliable to 0.1 volt. Other readings of V_4 gave 60,075 volts.

The greatest care was taken in reading V_1 and V_2 on the voltmeter coils, the low-tension voltage being of less interest. The small potential transformers may also have slight errors. The voltmeter coil in the 125,000-volt transformer should be perfectly correct, since operation is at half voltage and no load. It is thus seen that the error in the voltmeter coil of the 300,000-volt transformer is zero or so small as to be indeterminate by any ordinary methods, and therefore negligible.

On the other hand, the rise in voltage due to the capacity load is from 37,300 volts (measured on low voltage terminals) to 60,000 volts or 60.9 per cent (22,700 volts absolute).

These results show that the voltmeter coil is certainly accurate within 1/10 per cent, and probably much less on full load, normal voltage and zero power factor leading. It would undoubtedly be equally good on lagging load, but this is never encountered in practise.

Similar tests were made at no load. The following results represent the largest apparent error:

	V_1	V_2	V_3	V_4
Reading at 0 amperes....	59.9	59.8	91.6	95.8

High voltage from above

V_1 = 59,900
V_2 = 59,800
V_3 = 59,800
V_4 = 59,870

From all the readings taken the average error *seems* to be about + 50 volts at 300,000 volts *at both normal and zero load.* This could be produced by an excess of two turns in the high voltage winding of 12,000 turns, or represented by one-tenth of a division on the voltmeter scale.

As a conclusion from all the results it is claimed that the error is less than ordinary minimum errors of observation and instruments, and less than those inherent in any other known method of measuring high voltage.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

OPERATION ON THE NORFOLK & WESTERN RAILWAY

BY F. E. WYNNE

ABSTRACT OF PAPER

This paper describes the great advantages, from an operating standpoint, incident to the inauguration of electric service on the Elkhorn grade of the Norfolk & Western Railway Co. and why it is possible almost to double the capacity of the road by the use of 12 electric locomotives, instead of the 33 Mallet locomotives formerly in service.

THE ELECTRIFIED portion of the Norfolk & Western Railway lies chiefly in southern West Virginia between Bluefield and Vivian, as shown in the map, Fig. 1.The distance by rail is 30 miles (48.2 km.) but, "as the crow flies," Vivianis only 18 miles (28.91 km.) from Bluefield. The approximate profile in condensed form is shown in Fig. 2. Curves from 8 deg. to 12 deg. are of common occurrence and the average curvature is over 3 deg. The maximum grades eastbound are 2 per cent against 2.36 per cent with the load. For westbound trains the maximum grades are 1.1 per cent against and 2 per cent with the load. These figures indicate the severity of the service so far as alignment and grades are concerned. With the exception of Elkhorn Tunnel, the entire line is double-tracked, with considerable third track, numerous spurs and cross-overs and several yards. At the summit of the long grade up the west slope is a 3000-ft. (914-m.) single-track tunnel, part of which is on a 3-deg. curve. On the east slope, just west of Bluestone Junction, is a 700-ft. (213-m.) tunnel over the westbound track only.

The principal tonnage is coal, a portion of which comes from points west of Vivian. Between Vivian and Coaldale, the adjacent hills are honeycombed with coal mines which furnish tonnage both east and west. In addition, coal from branch lines is brought to the electric zone at Eckman, North Fork, Lick Branch, Cooper, Bluestone Junction and Graham. Of course, time freight and passenger trains also pass over the electric zone. The gathering of tonnage trains of eastbound coal

throughout the field is naturally accompanied by the delivery of empty cars from westbound trains to the numerous mines. Between Vivian and Coaldale, the line is operated as an elongated yard without intermediate telegraph stations. Communication with the load dispatcher may be had by telephone at each westbound signal bridge.

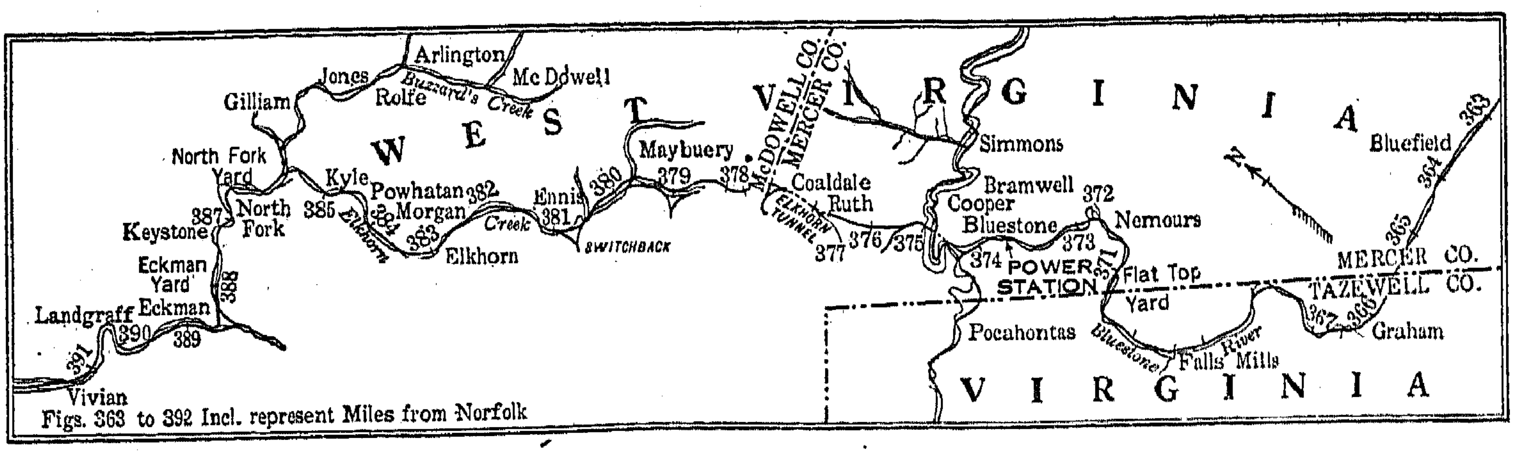


FIG. 1

The foregoing conditions apply with both steam and electric operation. In order fully to appreciate what electrification is accomplishing on the Norfolk & Western Railway, it is necessary to consider other general conditions which differ under steam and electric operation.

Until 1911, comparatively little coal was hauled west over the

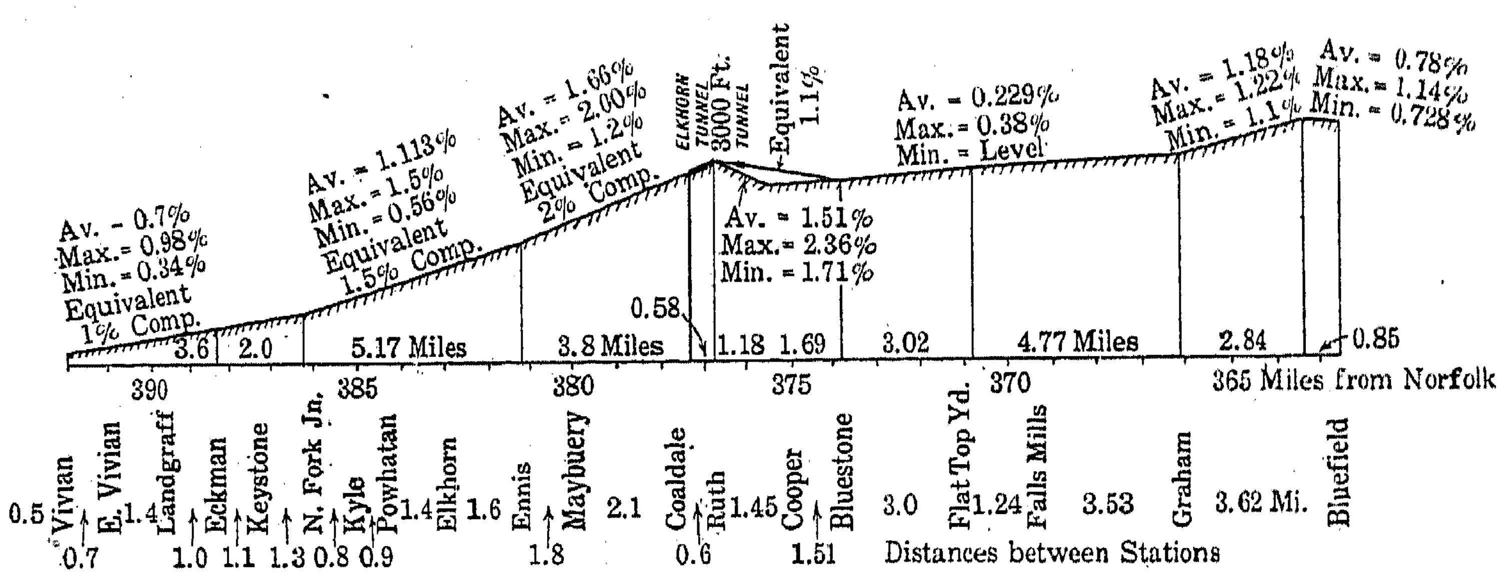
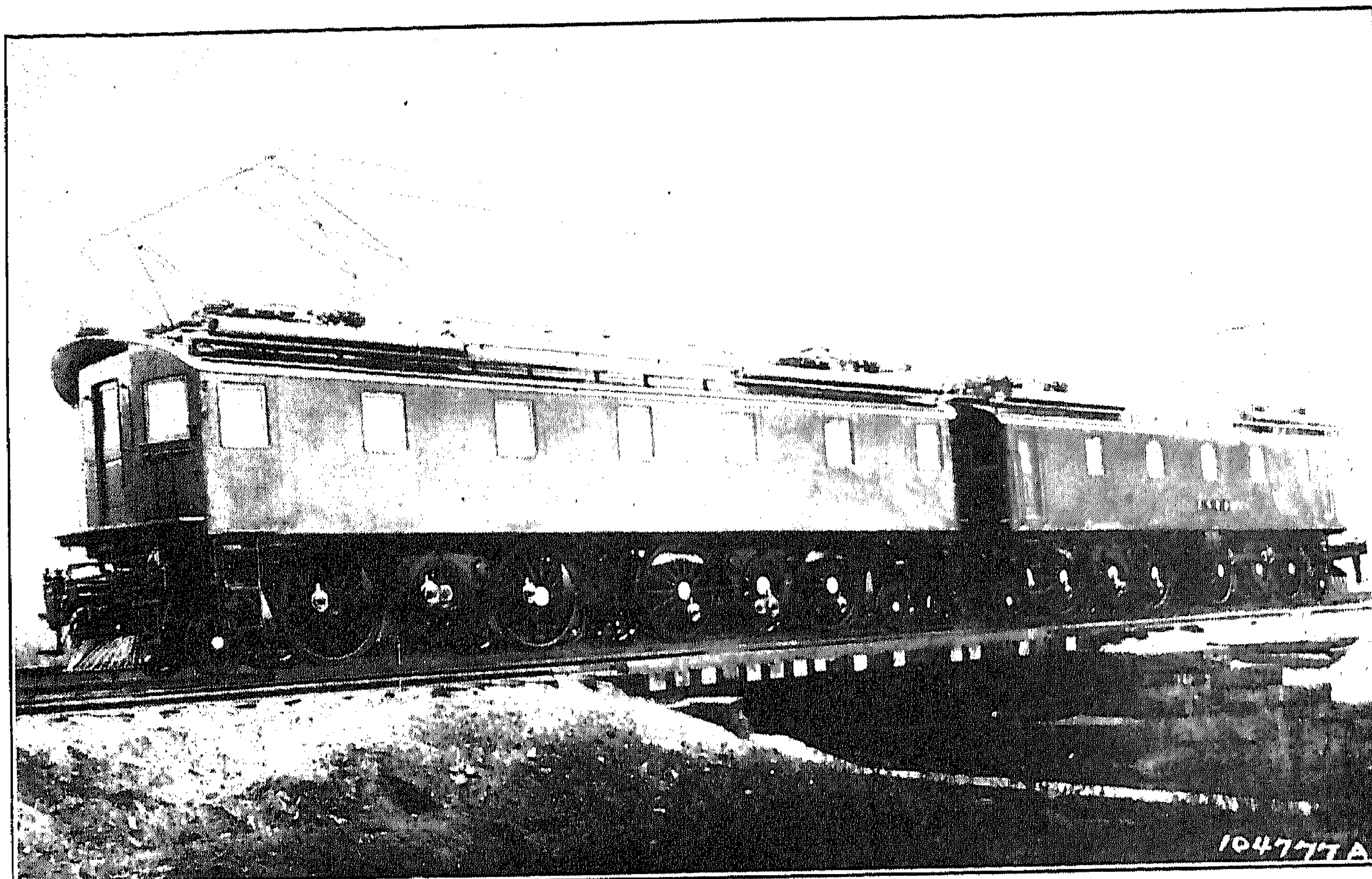


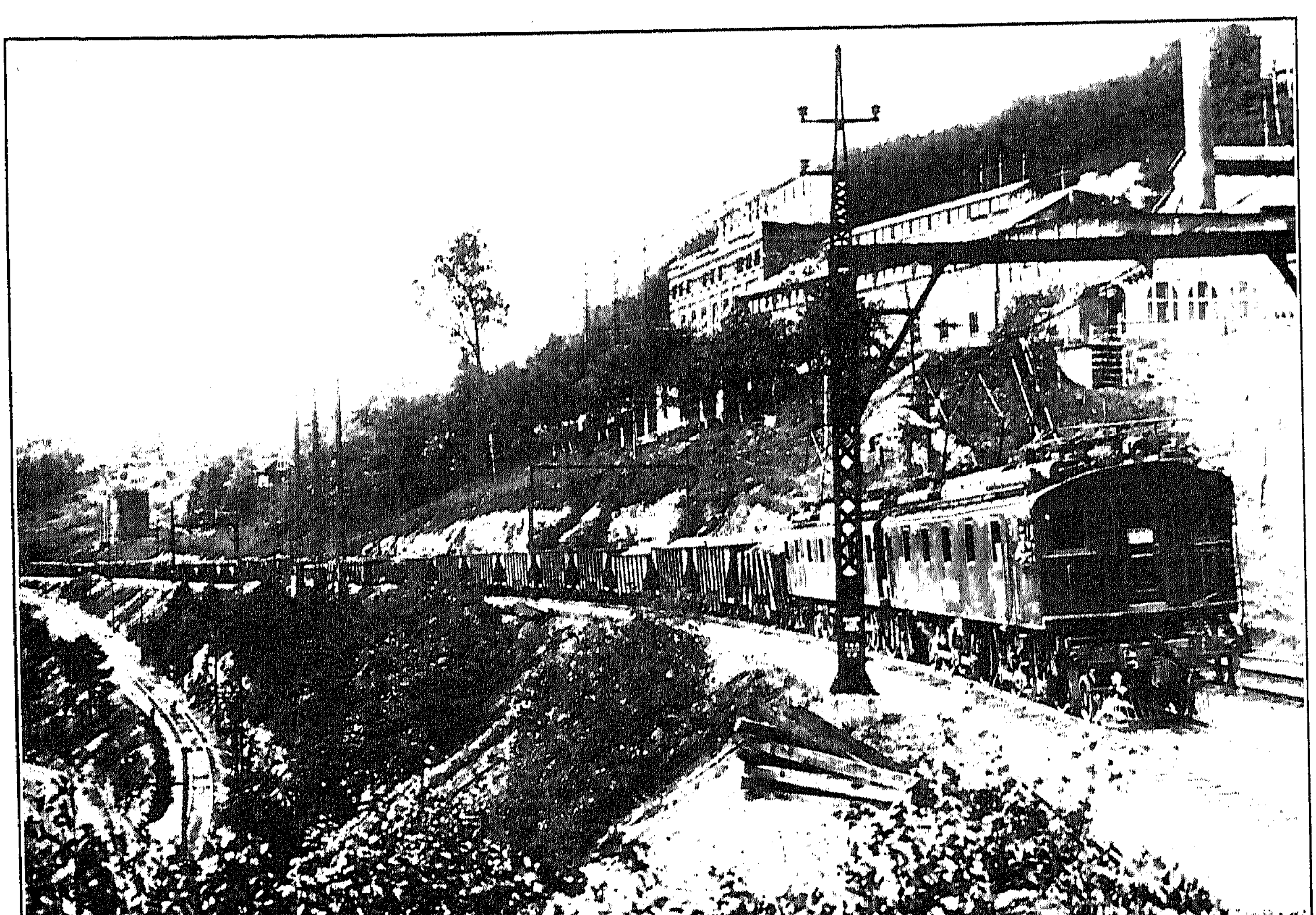
FIG. 2

hill. Eastbound coal constituted a decided majority of the total traffic. This was handled up Elkhorn Hill in 2360-ton trains with a Mallet locomotive, having eight driving axles, at the head end, a consolidation helper engine at the rear, and a consolidation pusher. Ordinarily the pusher locomotive did not work in the tunnel but remained with the train for emergency use. At Ruth, the east end of the long tunnel, the pusher cut off and returned west light or assisting in delivering empties on the west



[WYNNE]

FIG. 3—270-TON ELECTRIC LOCOMOTIVE USED ON NORFOLK AND WESTERN R.R.



[WYNNE]

FIG. 4—ELECTRIC LOCOMOTIVE AND COAL TRAIN ASCENDING GRADE AT SWITCHBACK

slope. From Ruth to Bluefield, the train was handled by the Mallet and helper. On this part of the run, the helper was necessary only for assisting the train up Graham Hill. This assistance might have been given by a pusher operating between Graham and Bluefield only, but for the fact that the helper was required for delivering westbound empties and it was impracticable to hold locomotives for this purpose at Ruth or Coaldale between the time of helping an eastbound train up Elkhorn Hill and the time a westbound train of empties arrived.

Westbound, the Mallet and helper ran light or with a train of empties (sometimes amounting to 125 cars) and occasionally picked up at Flat Top a small number of westbound loads. Practically all of the switching, picking up loads and setting off empties was done by the consolidation engines. As much of the tonnage originated along Elkhorn Hill, some trains started with less than the rated tonnage and filled out at one or more points. When this was necessary and also when delivering empties, the train was held by the Mallet at its head. On rare occasions, the Mallet helped in filling out the train.

A number of difficulties were experienced with steam operation. In starting on the hills, the rear engines, with steam in the cylinders, held the train until the head engine got its portion of the train under way. This period of standing under load ran from 30 or 40 seconds up to two or three minutes and often was repeated a number of times before the train got started. As the locomotives were rated practically at their maximum tonnage with good rail, slipping was a frequent occurrence when any condition reduced the adhesion. The slipping of either consolidation or one truck of the Mallet caused a loss of one-fourth of the motive power on the train.

On the west slope, eastbound locomotives took coal and water at two points, one of which was at times the starting point. Another stop for water was made at Cooper or Flat Top. The delays due to this were in themselves considerable, since at each coal or water station either two or three engines had to be cut off from the train and handled separately, the train being pulled up in the interval between supplying the head and rear engines. The attendant delays due to congestion were even more serious. At times, three or four trains followed each other closely, resulting in a delay at coal and water stations of about two hours for the last train of the fleet. Frequently further delays were encountered, because by the time the third or fourth train was coaled

and watered, it was necessary to clear the main line for one or more superior trains.

The low speed on grades with steam locomotives was another feature making operation difficult. On the heavy part of the grade from Ennis to Ruth the speed seldom exceeded six miles (9.6 km.) per hour and was often as low as four miles (6.4 km.) per hour. The fastest time freight was scheduled at only 9.5 miles (15.2 km.) per hour from Vivian to Coaldale and 13.3 (21.4 km.) miles per hour from Coaldale to Graham, while the fastest passenger train had a schedule of 19.5 miles (31.3 km.) per hour from North Fork to Coaldale.

The Elkhorn Tunnel was, to say the least, an unpleasant feature of steam operation, the grade being such as to require both the Mallet and helper to work through it going east. Although it was ventilated by fans blowing in the west end and the train speed was low, considerable smoke and gas were still in the tunnel when the helper and pusher went through. A little imagination can picture the conditions when a train stopped in the tunnel and all three engines had to work to start it.

Under the foregoing conditions, the maximum number of freight cars handled up Elkhorn Hill in one month was approximately 17,000. The average time of a round trip between Bluefield and the coal fields was 12 hours, and this constituted a day's work for the train crew.

Between 1911 and the time of electrification, additional Mallets with arches, superheaters and stokers were applied in this service and larger three-engine trains with Mallets in each position were operated. This afforded some relief, but 33 Mallets were required to handle the traffic in this way.

In 1911, no consideration was given to the electric operation of time freight and passenger trains. Now, in addition to handling coal trains and empties, the electric locomotives are pushing all eastbound time freights to Ruth and two of the heaviest eastbound passenger trains to Bluestone Junction.

One electric locomotive at the head and one electric pusher take trains of 3250 tons east to Ruth where the pusher cuts off and returns west light or assists in delivering empties. From Ruth to Flat Top, the head engine alone suffices. At Flat Top, the train is filled out to 4700 tons and an electric pusher is attached to assist the train to Bluefield. A regular day's work for a head crew is to take a train of empties from Bluefield to the west slope, return with loads to Flat Top, then run west light,

with empties or with west loads to the coal fields and return with loads to Bluefield. An Elkhorn pusher crew frequently handles five or six eastbound trains as a day's work, while a Flat Top pusher at times exceeds this on account of the shorter distance. With the electric locomotives, gathering loads and delivering empties may be accomplished equally well by either the head or rear locomotive.

On account of the length of train and curvature of the track, it is at times impossible to hear whistle signals. In starting a train with two engines, other means of signaling are used. The head locomotive releases brakes and lets the slack run back. As soon as the engineman on the pusher feels the blow resulting from this, he applies power and holds the train until the head engineman has applied power and gotten the front portion of the train sufficiently under way to permit motion of the rear locomotive and its share of the load. The period of standstill with power on for the pusher engine with this method of operation rarely exceeds 30 seconds and generally a satisfactory start is secured on the first attempt. This speaks well for the smoothness of the electric control, as the electric locomotives have less weight on drivers per ton of trailing load handled than was the case with steam locomotives. When slipping does occur on one truck, the loss of motive power is only one eighth of the total or one half of the proportion which occurred with steam.

The delays for taking coal and water have been eliminated from the trains which are operated entirely with electric engines, and have been reduced on those trains which are only pushed electrically. Consequently, there is also a great reduction in the time lost in secondary delays which were formerly produced by coaling and watering.

By means of pole changing, the electric locomotives are arranged for two speeds. The 14-mile (22.5 km.) per hour speed is used regularly for the heavy freight work, while the higher speed of 28 miles (45 km.) per hour is used for passenger trains, light engine movements and a certain amount of time freight operation. As a result, the speed of the coal trains has been more than doubled on the heavy grades and the average running speed for eastbound loads over the entire trip from the coal fields to Bluefield has been increased over 50 per cent. In passenger service, it is a common occurrence to pick up a train 20 minutes late at North Fork and put it into Bluestone Junction on time.

The dangers of steam operation in Elkhorn Tunnel have

practically been eliminated. The majority of the trains passing through this tunnel have only electric locomotives attached. Nearly all of those which do have steam engines on them are pushed through by the electrics at not less than 14 miles (22.5 km.) per hour with the steam locomotives doing very little work. How satisfactorily this is accomplished is indicated by the fact that in assisting time freights with a steam locomotive on each end, the head engine working and the rear engine idle, the electric pusher works through the tunnel with its windows open and without noticeable smoke or gas in the electric cab.

Certain features of the locomotives are notable in their effect on the handling of trains. The control is extremely flexible. Power may be applied to the motors of one truck on each half of the locomotive in starting. This is particularly advantageous with a light engine or a train of empty cars. In changing the speed, one half of the motors are changed at a time so that the entire tractive effort of one locomotive is never lost.

The arrangement for operating the rheostats is such that practically an infinite number of steps is provided for acceleration. The effect of unequal wheel diameters in unbalancing the loads on different motors may be readily counteracted. In case of wheels slipping, the load on the slipping drivers may be reduced until they again grip the rails, without reduction in the tractive effort developed at the drivers which are not slipping. In case of trouble, either a single truck or a half engine may be cut out without affecting the operation of the remainder of the locomotive.

The inherent regenerating feature is of great value in controlling the trains on down grades, and the fact that the speed down grade is constant and inflexible prevents the possibility of surges in the train which would result in broken draw-heads.

Considerable assistance in effecting a smooth stop is secured with trains having two locomotives approximately one-half mile apart by passing the load from locomotive to locomotive while backing off the control. To be a little more specific, when the head engineman desires to make a stop, he introduces a portion of the rheostat into the circuit of his motors. This slightly reduces the speed of the head engine and throws additional load on the rear locomotive. The latter, noticing the increase of load, realizes that a stop is about to be made and he too starts inserting resistance into his motor circuits, always, however, keeping his tractive effort up near the maximum. The front

engineman, on the other hand, inserts his resistance more rapidly, reducing the speed of his engine at a slightly greater rate than the rear engineman and allowing the latter to "bunch" all the slack in the train. As soon as the slack has all been bunched, the head engineman shuts off and if necessary makes a slight reduction with his automatic brake to bring the train to a stop. The rear engineman in his turn introduces more and more resistance into his motor circuits to keep from overloading his motors, until flush level has been reached. When he gets to this point, he holds his resistance constant until the train has been brought to a dead stop. He then makes a 30-lb. or 40-lb. application with his independent brake and having done this, throws his master controller to the off position.

Since electrification, not only has the eastbound traffic been very heavy but the westbound traffic from Flat Top is comparatively great when referred to that of 1911. Complete operating data are not available for publication at this time. However, a few general figures derived from the performance since the first of June, 1915, will serve to indicate what electrification is accomplishing. Compared with the Mallet locomotive performance of 1911, the despatcher's reports show that the electric locomotives are making eight times as many miles per train-minute delay due to locomotive failures in service. They further show that the electric locomotives have handled up Elkhorn Hill in a single day 50 per cent more slow freight tonnage than was handled by steam locomotives in the maximum day recorded prior to the summer of 1911. This was done with only nine of the twelve electric engines in service. From Nov. 1st to Dec. 17th, inclusive, there was no delay due to failure of electric locomotives in service. During this period the electric locomotives made nearly 45,000 miles (72,420 km.) with approximately 700 freight trains and 25,000 freight cars, each of from 60,000 to 180,000 lb. (27,215 to 81,646 kg.) capacity, eastbound up Elkhorn Hill. In addition, they pushed an average of two passenger trains per day up the hill and cared for an unknown quantity of switching service and westbound freight traffic. Presumably, the railway company will at some time in the future give statistics showing, better than is now possible, the heavy traffic and severe service which electrification is successfully meeting in this installation.

DISCUSSION ON "OPERATION ON THE NORFOLK AND WESTERN RAILWAY" (WYNNE) NEW YORK, FEB. 9, 1916.

A. H. Armstrong: The induction motor has one inherent characteristic, constant speed at all loads, that makes it of doubtful application to the haulage of trains over a broken profile. The speed of the motor can be varied only slightly except by changing its number of poles, a matter of doubtful expediency in its practical application to the operation of a train. We have been educated in steam railroading to expect the flexible speed characteristic of the steam engine, that is, slow running on ruling grade and proportional higher speed on the lesser grades and level track. Railroad practise therefore is more or less crystalized about the flexible speed operation of the motive power, and in adapting the induction motor to train haulage we are going against all previous ideas, and the continued operation of the Norfolk & Western Railroad will be watched with considerable interest as throwing light upon the adaptability of the induction motor to main line service.

The author gives little data in regard to the question of change of speed except that certain lighter trains will change from 14 to 28 miles per hour where the ruling grade is favorable. No reference is made to the fact that drag freight trains operate over a broken profile, and the inference is gained that such trains operate at a constant speed even on the considerable stretch of low grade track over which a higher speed would be permissible. With the steam locomotive or the d-c. motor locomotive, the sloping characteristic curve inherent in such motive power automatically provides for a change in speed inversely proportional to the gradient of the track.

Very little is said in the paper about regenerative braking although the induction motor inherently provides this feature. So much interest is attaching to electric braking on the Chicago, Milwaukee & St. Paul installation that I may be justified in commenting upon several operating facts found in connection therewith. The method of handling trains going over the crest of the grade and starting down is a matter calling for a considerable amount of skill. Having little to guide us in this direction I had hoped that the author would have brought out something more of the practise prevailing on the Norfolk & Western.

As the train surmounts the grade and the leading locomotive starts to descend no trouble is experienced in applying the electric brakes and in passing from motoring into braking unless the train is brought to rest and then re-accelerated on down grade. In starting on a down grade it is sometimes difficult to change from motoring into braking without introducing the possiblity of breaking the train in two. One method of minimizing this trouble is to tip the retainers on a certain number of the leading cars of the train so that an application of air will result in bunching the slack on the leading locomotive.

The change from motoring to braking can then be effected without occasioning a surge. It has even been possible to hold back a 3000-ton train on a 2 per cent grade with electric locomotives in different parts of the train both braking electrically. No exact method of handling the train down grade has as yet been established, but the greatest success has attended the use of electric brakes and the energy returned to the line has been approximately 15 per cent of the total average demand of the first engine division electrified on the Chicago, Milwaukee & St. Paul road.

It is, of course, understood that retainers are kept in use only during the initial period of changing from motoring into braking, the air is then allowed to leak out and the train handled in its entirety by the electric brake. The electric brakes will hold back the entire train provided the locomotive weight on drivers will furnish the necessary tractive effort without exceeding a coefficient of adhesion permissible with the condition of the rails. For example, on ore roads where the grade favors the load it is current practise for the locomotive to handle a train down grade which is very much heavier than the same locomotive could haul up grade. This is made possible by the application of air brakes to all cars, and if an attempt is made to hold back the train by electric brakes on the locomotive it would demand such a high tractive effort as to exceed the ability of the locomotive to hold the train back and the wheels would slip. With such trains therefore it is necessary to supplement electric brakes by a certain amount of air brake application or else install locomotive capacity greatly in excess of what would be required to haul the empty cars up the grade on the return trip. The combined use of electric and air brakes introduces some new features which are not as yet reduced to a standard practise, but undoubtedly the constant speed characteristic of the induction motor introduces a handicap where electric braking is supplemented by air brakes, and this is due to the small latitude which such motors permit in speed variation. The d-c. locomotive is much more readily adapted to the combined use of electric and air brakes, as the speed at which electric brakes can be applied extends over a considerable range and thus fits in better with the combined use of electric and air brakes in cases where the electric locomotive has not sufficient weight on the drivers to hold back the trailing load on down grade. The constant speed characteristic of the induction motor therefore may prove to be a serious handicap not only during the period of motoring over a broken profile but also during the regenerative period down grade where the combined use of electric and air brakes may be enforced.

Some reference has been made to the question of wheel correction, that is, the induction motor being a constant speed motor will operate at a constant rotative speed while the locomotive speed will be proportional to the wheel diameter. When

all wheels are new any two locomotives may be coupled together in the same train and all motors run at the same speed. After the tires have been turned, however, there might be coupled to the same train two locomotives having tires of different diameter, in which case a constant resistance must be interposed in the motor secondary geared to the larger wheel diameter in order that the wheel peripheral speed shall conform to that of the smaller wheel diameter. This constitutes a loss in efficiency which is peculiar only to the split-phase or induction motor type of locomotive and adds to the burden of locomotives of the Norfolk & Western type which already have a very low efficiency due to the losses in transformer, phase converter, gears, jack shaft, side rods, etc. It will be interesting to know the efficiency of these locomotives especially after they have been operated for a sufficient period to call for the turning of tires.

R. E. Hellmund: The regenerative control of the Norfolk and Western locomotives, was found to work much easier and better than had been anticipated. When the heavy train is pulled up the hill and passes the crest, it is only necessary to keep the power on the locomotive in the regular way and the locomotive picks up the regenerative load car by car automatically and the engineer has practically nothing to do. You can stand on the locomotive and watching the ammeters observe the increase in regenerative current as each car bumps up against the car in front of it; there is a succession of these little bumps, and you can practically count the cars as they are picked up by the locomotive. It works very smoothly and without any trouble. In fact, some of the operation which originally it was not contemplated to do by electric braking is now being done in this manner, because it is much easier than the air braking.

In the control of the locomotive, the water rheostat is of some interest, in so far as its control is different from the type of controller commonly used on electric locomotives. We are all accustomed to have a master controller which is worked by notches, to increase the voltage on the motors or change the connections. In this particular locomotive the water in the rheostat is lowered and raised by means of a handle, the operation of which is somewhat similar to the operation of the throttle lever of the steam locomotive, and it seems that the steam engineers find that very convenient and much to their liking

As to the limiting speeds of the induction motor, which have been considered so much of a disadvantage, we find more and more that this feature can hardly be considered as such. About six or seven years ago whenI first saw three-phase motors operating in Italy, I was very much worried about their disadvantages. I was told however, that as an actual fact, the service could be handled better and easier than with steam, and while steam trains were frequently late on the steam lines the electrical trains hardly ever were late; this is because variable

speed locomotives will lose time with overloads, while the three-phase motor always runs at the same speed and there is less chance for losing time.

Then, of course, there is the possibility of losing time in the stations for various reasons, and the argument is that such time cannot be made up by the constant speed locomotives. It is to be considered in this connection that most railway equipments are worked about to their limit nowadays, and whether you have the series characteristic or the constant speed characteristic, you cannot make up time except by shortening the coasting period. This can be done with a three-phase motor as well as with a series characteristic motor. If you want to make up time, the only chance you have in either case is to make it up by keeping the power on longer. For this reason it seems that the slight difference between the two motor characteristics apparently does not grow to be a great disadvantage in actual practise. In Italy they handle passenger traffic to a very large extent with three-phase motors, and they are altogether satisfied with the limited speed characteristic.

Francis H. Shepard: Railroad service on the Norfolk and Western is far from toy railroading. These locomotives weigh 270 tons, and to give you an idea of the amount of power handled, with an ordinary train accelerating on the grade the power runs from 8000 to 9000 kw. per train. On certain accelerations which have been made for demonstration purposes, the power reached 12,000 kw., and on a single locomotive, also for demonstration purposes, on the 28-mile connection, 8000 kw.

In handling a long train, I might say that some twenty years ago I lost my respect for the strength of railroad equipment. Down in the Baltimore and Ohio tunnel we broke trains in two as though they were a string of egg-shells. A train is not an inflexible structure; the least little jerk on the controller may tear the train in portions, and one of the necessities in handling heavy trains, and particularly in getting satisfactory performance with the train, is to have absolute control of the motive power. The more refined control of the train you can get the better off you are.

It is a serious matter for a Mallet pusher to slip at the rear of a train, in that it commonly results in breaking the train into two or three parts. When you break a train in two on these grades with cars with lading which weigh 130 tons each, it is because no draw-bar or draft rigging can stand the surge and shock. For instance, on one occasion on the Norfolk and Western inadvertently the trolleys were lowered on the rear or pusher locomotive; the power was cut off thereby, and the train broke into three parts. These locomotives are, of course, interesting to everyone who sees them and rides on them. This accident happened because the conductor seeing these levers wanted to know their function and whether they were operative, and was told "No, they are all cut out, except on the operating end." That was

the fact, except for the trolley down button. That was the very one he pushed.

The operation of the liquid rheostat has been amazingly successful. There are many operations which take place in handling these heavy trains which do not follow the pictures we ordinarily consider railroad operations are governed by, the speed-time curves of the designing engineers.

It is not uncommon for a train to have stuck brakes, to have an excess tonnage, or to require a slow-down movement, and the facility and capacity of the water rheostats to secure these abnormal operations is, as I have said, amazing. The curvature on the Norfolk and Western is so great that with the long trains it is quite impossible to pass the customary whistle and other signals from the head to the rear of the train. In the operation up the grade, the head engineer gets a " slow " order, the pusher engineer has no knowledge whatever of this, the head engineer shifts his load by inserting resistance, the rear engineer receives immediately a corresponding increment of load, he also in turn shifts, and thus they may drop down to half speed, or less than half speed, and then when the slow order has been satisfied and they wish to accelerate up to full speed again, the head engineer opens up; the rear engineer sees he is opening up, so he does likewise, and the whole operation is carried on without any surge to the train whatever.

The result of this is that extreme facility in operation is secured and a very material decrease in damage to equipment over that inherent to a variable speed locomotive such as one operated by steam.

As to the inflexibility of the induction motor, a few years ago I agreed entirely with Mr. Armstrong's opinion, as expressed this evening, but I must confess that I have changed, and that change in my position has been very largely governed by our operation and analysis, together with contact with railroad men. These motors operate so satisfactorily that the dispatchers and tower men will despatch one of these constant speed trains ahead of a passenger train, definitely figuring on only a minute or two leeway, and know that the train is going to clear. You thus get the capacity out of the railroad because the dispatchers and tower men know that trains will start and clear in a certain number of minutes and that the first-class trains will not be held up. In the case of steam operation, when they give a train a clear track they do not know when it is going to clear.

The operation of the induction motor for regeneration is exceedingly simple, and the ease with which it is operated has resulted in the men using the air brake only when they really have to, that is, to come to a standstill. Even in light train or single locomotive operations it is not unusual for them to regenerate, because it is the simple and easy way of governing the train.

Every one who has ridden on a mountain grade knows that

the dropping of a train down a grade is not at constant speed or anywhere near constant speed. The train hunts in speed up and down the grade, and before you get the last service application to the brakes you are always more or less concerned, and greatly relieved when you know that you have reached the foot of the grade. In swinging over to constant speed regeneration, while going over the summit of the grade, the operation is simply the switching of the levers to secure a little better operating characteristic on the locomotive,—it is not really essential,—and we take down a train of 103 cars, which is a pretty sizable train without touching the air and would not spill a drop of water out of a glass in the caboose.

Swinging into regeneration from start, on a down grade can be accomplished with about the same facility. There was originally some concern as to how we would tip the train over the summit, whether the head engine would not give a terrific surge to the train, but as I say, this is handled with great smoothness.

In taking a train down a mountain grade with this system, you feel as though it were tied; that is, the sensation when you go down with a constant speed locomotive, no running up in speed and no occasion, therefore, for any excess in tractive effort above the holding tractive effort. There is a vast difference between the adhesion required to start a train on a grade and the adhesion required to hold that same train going down. a grade. By that margin this inflexibile characteristic is advantageous.

We are taking 3250-ton trains down a pitch of 2.4 gradient from the head end without touching the air. This exceeds the adhesive limit you would ordinarily assume. This is done regularly, a dozen or twenty times a day. If, for any reason, the rail is bad, you can very readily touch up the train with a light brake application, and take part of the retarding effort with the train brake. I may say that retainers are not used, they have not been found necessary to secure smooth control of the retardation.

If the engineer should for any reason during regeneration handle the train brakes improperly—and, by the way, there is more opportunity to wreck a train by improperly handling the air-brakes than in almost any other way—the constant speed characteristic in the induction motor shows its great advantage, for the speed of the train is absolutely held until the train brakes have full control of the train. The train brakes must positively have control of the train before the locomotive holding that train loses its holding power, and therefore it is a perfectly safe and smooth operation, simply to shut off the controller.

In bringing the train to a stop on the grade, the brake application is always made first, and as soon as the motor ceases holding, the train is under full control by the air with auxiliaries fully charged, there is no chance of running up, and the train is slowed down from its constant speed of fourteen miles an hour.

The men who handle these constant speed motors are delighted with their inflexible speed characteristics and it is noteworthy that on regeneration there has never been a case of slid wheels or train broken in two.

B. A. Behrend: We have discussed the subject of the electrification of trunk lines for the past ten years. The situation seems to be about the same today as it was ten years ago in regard to unanimity of opinion as to the best system available. Mr. Wynne's paper and Mr. Shepard's able discussion of it have demonstrated without doubt that single-phase generation and single-phase distribution to single-phase-three-phase locomotives has been successfully executed on the Norfolk and Western Railway. Mr. Armstrong's discussion has reminded us that high-voltage d-c. distribution to high-voltage d-c. locomotives can be, and also has been, successfully carried out on a large scale. We are further aware that single-phase generation and distribution to single-phase locomotives has worked out successfully on the New Haven Railroad. It remains only to raise the point whether the difficulty of three-phase distribution is such as to make impossible the use of three-phase generation, three-phase distribution, and three-phase locomotives. Unless the use of two trolleys, which three-phase distribution necessitates, is as prohibitive as the railway engineers make us believe, it would not seem permissible to resort to the additional complications of adding on each locomotive a single-phase three-phase synchronous converter. It must always be borne in mind, as has frequently been stated since the advent of the single-phase railway, that the generation of single-phase currents is a very uneconomical process, involving problems of design of single-phase generators which are very difficult of satisfactory solution. It must always be borne in mind that the best single-phase generating plant conceivable, if it were to be utilized for three-phase generation, would, electrically, almost be doubled in capacity merely by the utterance of that magic word three-phase for single-phase. After all, then, perhaps, such great engineering achievements as the electrification of the Norfolk and Western Railway, or the Chicago, Milwaukee and St. Paul Railway, must be described as the least unsatisfactory solution of a difficult problem rather than as the most satisfactory solution that can be devised.

W. I. Slichter: Whether we believe in one system or the other, I think that all of the systems have shown that the electrical engineer by one system or another can move the freight and the passenger traffic on big trunk line railways more economically, more reliably and more satisfactorily than the steam locomotive. Each system, as Mr. Behrend has said, accomplishes the result, and whether it is the best system in the end, I believe nobody is able to say any more that any one can say any particular steam railway has the best system.

In this system we have the application of three-phase motors to heavy work. I think we all concede that this heavy

coal-bearing traffic is the best place in which the three-phase motor could be put. The three-phase motor has the great advantage of being able to regenerate power with the simplest and easiest connections. It has the disadvantage that it is a constant speed motor, and that it is very sensitive to changes in voltage. That is one point on which I would like to question the author,—what variation in voltage at the locomotive has been experienced in practise, and whether this loss in voltage has been found to be of any great disadvantage. We are aware that the torque of the induction motor decreases as the square of the voltage.

The phase converter is a very interesting piece of apparatus, which meets the railway operator's criticisms of the polyphase motor, in being able to take single-phase currents and convert them to three-phase currents and give the polyphase induction motor the currents it needs. At the same time, it adds one more link in the chain as to reliability and as to drop in voltage. It adds certain increase in weight, and we have then the question—Is it worth while?

This regeneration is of very great value in saving equipment by holding the trains on the curves, but it requires additional care in management. On this road is the traffic sufficiently great so that the regenerated energy from trains going down grade may be taken care of adequately by trains going up grade, or is some regulating device provided, so that in case trains are only going down grade and none going up grade, the excess energy will be absorbed somewhere?

R. E. Hellmund: The previous speaker made reference to the sensitiveness of the induction motor to voltage variations. It is quite true that the torque of the induction motor varies with the square of the voltage, but on the other hand it is not at all difficult with these large motors to design them for torques very much in excess of the rated torque. With the Norfolk and Western locomotives, for instance, I believe the slipping point of the wheels is about, I should say, 200 per cent of the rated load of the motors, while the motors are good for 400 per cent at normal voltage. Thus you can readily see that assuming 20 per cent voltage drop, or even 25 per cent, and a corresponding drop of 40 or 50 per cent in torque, the motor torque will still be in excess of the slipping point of the wheels, in other words, there is always plenty of torque to get started. After the motors are once up to speed, the variation of voltage simply means that the load current will change; it will increase inversely proportionate to the voltage; however, the increased copper losses caused thereby are largely compensated for by decreased core losses, and for that reason it is a matter of fact that the induction motor will run with pretty nearly the same temperature with voltage variations of 10 to 20 per cent. Of course, that depends somewhat on the detail design, but as a rule there is not much difficulty in taking care of the voltage variation.

Charles F. Scott: We have before us certain railway performances. In steam railway operation there is no performance equal to that which has been described here this morning. Trains of over 3000 tons have been run up grades at the rate of 14 miles an hour, train after train, in regular and heavy service. After the long development of steam locomotives, a dozen or so of the electric locomotives are doing the work of something like thirty of the best steam locomotives that could be obtained. The electric train service is something like twice what is possible with steam, *i.e.*, the highest speed and power found practicable in steam operation have been doubled in electrical operation and the capacity of a congested track has been doubled.

In comment, what are some of the questions which are asked? Some inspect the outfit with a sort of microscope and say, "This might be different, or that might be different." One of the gentlemen who took part in the discussion this morning, is artistically pessimistic. He says about the generator—"Why, if it were a three-phase generator, you could get twice as much out of it." Surely, but the generator is a small part of this system. Moreover, is not the generator on the basis of kilowatts output per pound of generator, giving a performance comparable to that of any generator, a dozen years ago?

A question has been raised about two trolley wires. Would it not be better to use them instead of putting in the phase converter? Is this not a simple matter of detail, a matter of compromise, between the mechanical objections to running the extra trolley, and the objections to putting a little more apparatus on the locomotive? It is really calling on the electrical system at the two ends to bear the brunt of the mechanical objections to the additional trolley. If the three phase system had been employed on the line as well as the locomotive there would have been required two overhead high-voltage contact wires instead of one; two current collecting devices on each locomotive instead of one; two oil switches instead of one; transformers for three phases instead of one; a three-phase motor for driving the blower and compresser instead of a phase converter which serves the double service of phase converter and motor.

It has been alleged that the induction motor does not permit a higher speed on level track; but in this particular case the change in the number of poles secures a speed of 28 miles, or double that employed on the grade. This is a higher speed than would ordinarily be obtained from a direct-current equipment.

True, electrical engineers do not agree among themselves, on all plans and details. But, our variations are no wider than those in steam locomotive practise. The problems which the steam locomotive designers have been working on for nearly a century, have been solved electrically. A kind of apparatus was required which had not been built before, combining a great many new types of elements, and a great many elements

of common type, but designed in new fashion, so that they can work together on a large scale, and we utterly outdistance steam practise.

If the new locomotives are hauling more coal and giving railway service superior to any ever given before, it is a little uncomplimentary, at least, to say—"Well, that is probably the least unsatisfactory thing that could be done." Of course it is, if we have done the best thing possible, exceeding anything which was done before, of course it is the "least unsatisfactory." That particular system is best which in a given case performs the service at the least cost.

William Arthur: When you stand back and look at what has been accomplished on an electrification such as the Norfolk and Western, you get a new perspective. Talk, such as we have heard about retainers, whether single-phase generation was highly efficient, when compared with some other system, and other relatively unimportant details seems to me very largely immaterial. The weight of the locomotives too, has been compared and one member referring to the locomotives on the Norfolk and Western, mentioned the fact that they had to carry the phase converter. A locomotive must possess weight in order to fulfill its functions. No one can conceive of a weightless locomotive doing any work. You have to get the grip on the rail and sufficient power must be applied to the wheels to maintain the adhesion which the engineers decide is necessary. That today can be done with any system. The question of the weight of the locomotive as between the various systems is today relatively unimportant, although a few years ago when we had only low voltage, direct-current and single-phase, to compare it was of more importance and there was then usually a difference between the weight of the two types for the reason that the low voltage d-c. motor considered alone, will always be lighter than a motor of the same capacity but of the single-phase type.

This is not true to-day of the locomotives as a whole. The problems entering into the weight question, the space problem, the means of ventilation, etc., are such that taking the modern locomotives of the various types and comparing them, there is but very little difference between them. To-day locomotives can be built on any system, particularly for freight service, which have practically the same weight.

H. M. Hobart: I do not share Mr. Behrend's pessimistic view that it is a question of choosing the least unsatisfactory of two very unsatisfactory solutions. I think it is a question of which is the most satisfactory of a variety of excellent solutions. On the other hand, I do not agree with Prof. Scott, and some others, that engineers, can say that the sole test of success is technical success. Engineers must continue to strive to get the best system possible. Because a system works and works excellently, it does not mean that it is the best system, and we will all admit

that in the long run the object is to find the most excellent system, and that is decided on the basis of dollars and cents.

It is surely not necessary at this time to review the distinguishing features of each particular system, three-phase, direct-current and single-phase. What has always exasperated me is that we did not sit down ten years ago, or earlier, and actually settle on paper that which could have been absolutely and conclusively settled on paper. I do not for my part see why it should have taken engineers ten years to conclude that the single-phase generator is out of all proportion heavier and more expensive for its output than the three-phase generator. Right up to very recently, whenever in papers or discussions I assigned to the single-phase generator any approach to its actual and now widely admitted degree of inferiority, it was stated that my representations were seriously exaggerated.

Mr. Behrend estimates a superiority of the order of 2 to 1 for a three-phase as compared with a single-phase generator. As I have already stated, it has been very difficult to find recognition of the fact that the inferiority of the single-phase generator is of such magnitude as to be of any consequence. Mr. Behrend, however, recognized this at an early date and it is of interest to recall his statement of ten years ago in an article in *Cassier's Magazine* to the effect that: "The very much reduced output of both generators and motors, if operated single-phase; the reduced efficiency; the impaired regulation; the increased heating and less stability of single-phase motors and generators, connected with the increased cost resulting from the greater amount of material required; these form the main reasons which induce me to call the recent attempts which have been made in the utilization of single-phase currents, a forced idea."

Professor Scott, in alluding to the inferiority of the single-phase generator said: "What of it, it is only one link in the system?" In reference to the greater cost of a locomotive having a phase converter on it, we might say "What of it, it is only one link in the system?" But they all count up, and we must take account of each link. We are not concerned to get the most novel system, or to get something which technically works with great satisfaction, if it is economically inferior. It is quite incumbent on some one, and I have taken upon myself that duty, to remind you of what we all know very well, that the engineer must strive to obtain the most economical result.

F. E. Wynne: I agree with Mr. Hobart that it is very desirable to obtain some figures regarding the economics of operation of all electrifications which have been made. On that question, if he will refer to the last sentence of the paper, he will note that we make the following statement: "Presumably, the railway company will at some time in the future give statistics showing, better than is now possible, the heavy traffic and severe service which electrification is successfully meeting in this installation." When I wrote that I had in mind also the economies of operation

on this road. Such information was not available for publication at that time.

One of the best features in the induction motor is its constant speed qualities, which insures adherence to schedules, which the variable speed motor does not necessarily do. Like Mr. Shepard, I used to be very strongly on the other side of the fence, and thought there was no possibility of an induction motor being of any use on a railway. Following the operation of the Italian State Railways, and also having seen the operation on the Norfolk and Western, I must say that I am convinced that it has a very good field, and that the constant speed characteristic is not altogether, in fact, it is very far from being altogether, a disadvantage in this type of engine.

Mr. Shepard stated that the retainers are not used at all on this road for assistance in braking. If any other system of electrification requires the use of retainers in order to get over the brow of the hill, it is certainly a serious handicap to that system. The correction for wheel variation which is mentioned as a possibility has not yet been found necessary in practise. So far the individual motors take whatever unbalancing is found due to difference in wheel diameter. It may be found desirable to stand for the slight rheostatic losses entailed at a later date when the wheels get worn more.

Mr. Behrend's question, which he said he would ask if he dared, was why this installation was not three-phase throughout; that is, three-phase generation, transmission, conversion, distribution, and propulsion. There are two ways in which I think that can be best answered—one is that the Great Northern Cascade Tunnel, three-phase installation, has been in operation for a number of years, and since that time I know of no other case where a three-phase installation has even been proposed, not to say, been installed, in this country. Second, there seems, as Mr. Behrend mentions, to be a decided prejudice against two trolley wires in this country. I think if he would go over the Norfolk and Western electrified zone he would probably also become prejudiced against the use of two wires over each track. It would be an exceedingly complicated piece of overhead work, and as there are nearly one hundred miles of trackage to be handled I hardly see why we should handicap this one hundred miles of track and the problem of collection for the sake of getting two or three more efficient generators and eliminating a certain piece of apparatus from the dozen locomotives.

Prof. Scott's characterization of the split-phase locomotive as using the electrical part of the system to relieve the mechanical part is, I think, very happy. He also inquired as to whether the performance as measured by the train sizes and speeds had ever been equalled in steam operation. So far as I know, it has not. Very frequently there have been larger trains handled, but I do not think that the combination of train size and speed on such grades has ever been secured elsewhere.

Prof. Slichter asked what variation in voltage occurs at the locomotive. So far as I know, the variation has not exceeded 25 per cent, and I think the track capacity together with the distribution layout will hardly ever permit it to exceed this value.

Prof. Slichter also inquired regarding some kind of a shock absorber for regenerated energy. The traffic on any railway of necessity at times will have valleys where there is no load being taken from the power house—it is not peculiar to the Norfolk and Western—and consequently in any system utilizing regenerated energy and supplying railway load alone, it will be necessary to provide at the feeding points, either substations or power house, a rheostat which will absorb the regenerated energy when there is no other load on the line. Such a rheostat is in use on the Norfolk and Western and operates a few times in the course of a day.

In this discussion, there has been a tendency to emphasize details and to determine which present system is the least disadvantageous, or whether any one is the most advantageous. I think that is a biased point of view to take. We are all trying to improve the art of electric railroading, and I believe that every one here will agree that an art which has only thirty years' of history behind it, is not yet perfected. There is probably no one electric railroad system that is as yet perfect. We hope that some day the various systems may be perfected, and that it may be possible to determine for individual cases, which is the most advantageous system; and if such a thing is possible, we should like to see a single system on which we may standardize. I think it will be some years before we get to any such point. Electrification is entirely too new and young at the present time.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE

BY A. J. HALL

ABSTRACT OF PAPER

This paper describes the liquid rheostat in locomotive service, giving in detail the arrangement of the mechanical parts and means for controlling it.

LIQUID rheostats in locomotive service were successfully used for the first time in this country to control three-phase induction motors on the Norfolk & Western locomotives, which have certain operating characteristics resembling very closely those of the steam locomotive, especially the manipulation and the amount of abuse they will stand without being materially damaged.

The principal functions required of these rheostats are as follows: To cut out the resistance in the secondary circuit of the main motors while accelerating, or regenerating; to compensate for the slip between the different pairs of motors, due to the variation in the size of drivers, and to make and break the current in the main circuit to reduce wear on the primary switches.

The main circuit schematic diagram, showing the connections of the liquid rheostat in conjunction with the rest of the equipment is shown in Fig. 1.

The rheostats are operated in pairs each pair having one operating mechanism, storage reservoir, cooling tower and circulating pump.

Figs. 2, 3 and 4 show the mechanical structure of the liquid rheostat, which consists of one main casting, which is divided into four compartments, a central one and three arranged in triangular form around it. A set of electrodes is mounted in each of the three outer compartments. In each compartment, one electrode is grounded to the side of the main casting, and the other is suspended from the top cover and insulated from ground by three porcelain insulators. The rods which support the latter electrode are connected by copper straps on the outside

of the cover. Each set of electrodes is connected through a pole change-over switch to the secondary of a three-phase motor. The electrolyte furnishes resistance between the insulated electrodes suspended from the cover, and those grounded on the side of the main casting, thus making the main casting the common point of the star connection. The center compartment provides space in which a steel tube, T (Fig. 3), which can be raised or lowered, acts as an overflow pipe for the liquid. The height of the liquid in the rheostat is thus varied by the position of the overflow tube. The electrodes are made up of iron plates.

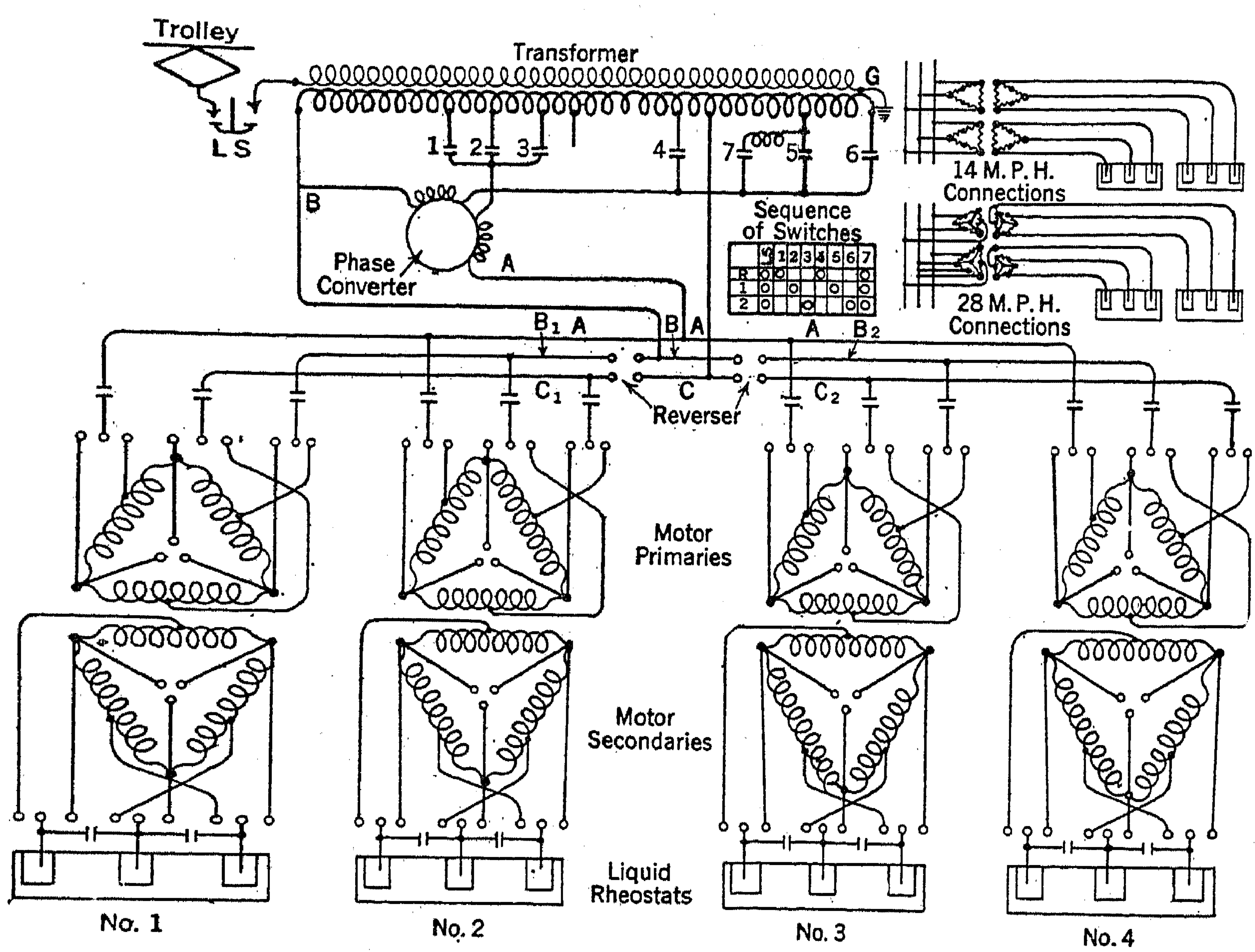


Fig. 1—Schematic Diagram of Main Circuits of Single-Phase Locomotive with Liquid Rheostat Control for Induction Motors

The effective area gradually increases and the resistance in the circuit decreases as the surface of the liquid arises.

Two of these rheostats are mounted on top of the main supply tank containing the electrolyte, which consists of a 0.5 to 1 per cent solution of anhydrous sodium carbonate (NA_2 CO_3). The intake to a pump which will circulate approximately 300 gallons (1135 l.) per minute is connected to the supply tank and the outlet is divided into two paths which lead into the bottom of the rheostat castings mounted on top of the supply tank. The upper portion of the regulating or overflow tube (T) is about three in.

(7.6 cm.) smaller in diameter than the lower portion, so that when this tube is at its lowest position, there is a space (S) around the valve for the liquid to flow through from the rheostat to the supply tank without coming into contact with the electrode. When the overflow tube is raised, the upper portion of the larger part of the tube comes in contact with the valve seat, preventing the liquid from flowing through. It then flows over the top of the tube, raising the level of the electrolyte in the rheostat and

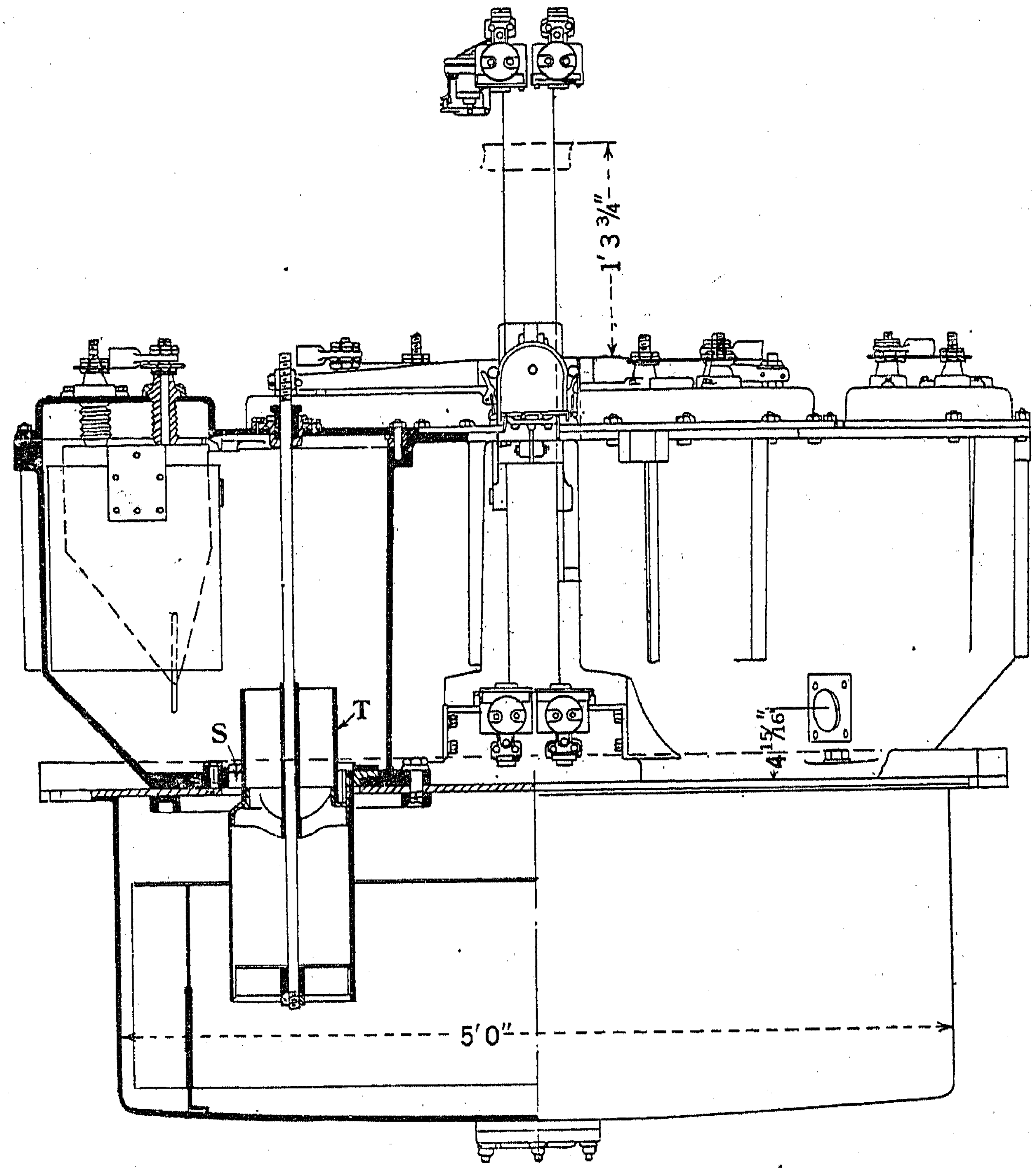


FIG. 3—PARTIAL SECTION OF LIQUID RHEOSTAT

submerging a portion of the electrodes. This position is called the "flush-level" of the rheostat.

The operating mechanism in the center of the rheostat is controlled by a balanced pressure operating mechanism which is mounted above and between the two rheostats. The crossarm extending from this mechanism is connected to each of the two overflow tubes by a rod. Thus the raising or the lowering of this crossarm raises or lowers the level of the liquid, which in turn

varies the surface of the electrodes submerged. The entire control of the locomotive centers about the liquid rheostats, which are so designed that the engineman can bring his locomotive up to speed with practically an infinite number of steps.

The master controller, Fig. 5, consists of two separate and independently operated drums, neither of which is mechanically interlocked with the other, but both are interlocked with the reverse drum, so that both handles must be in the "off" position before the reverse drum can be thrown. The speed drum has four "on" positions to set up the required combination of pole change-over drums, reverser and primary switches. The two main positions are the 14-mi. (22.5-km.) per hr. and the 28-mi. (45-km.) per hour. Between the 14-mi. (22.5-km.)

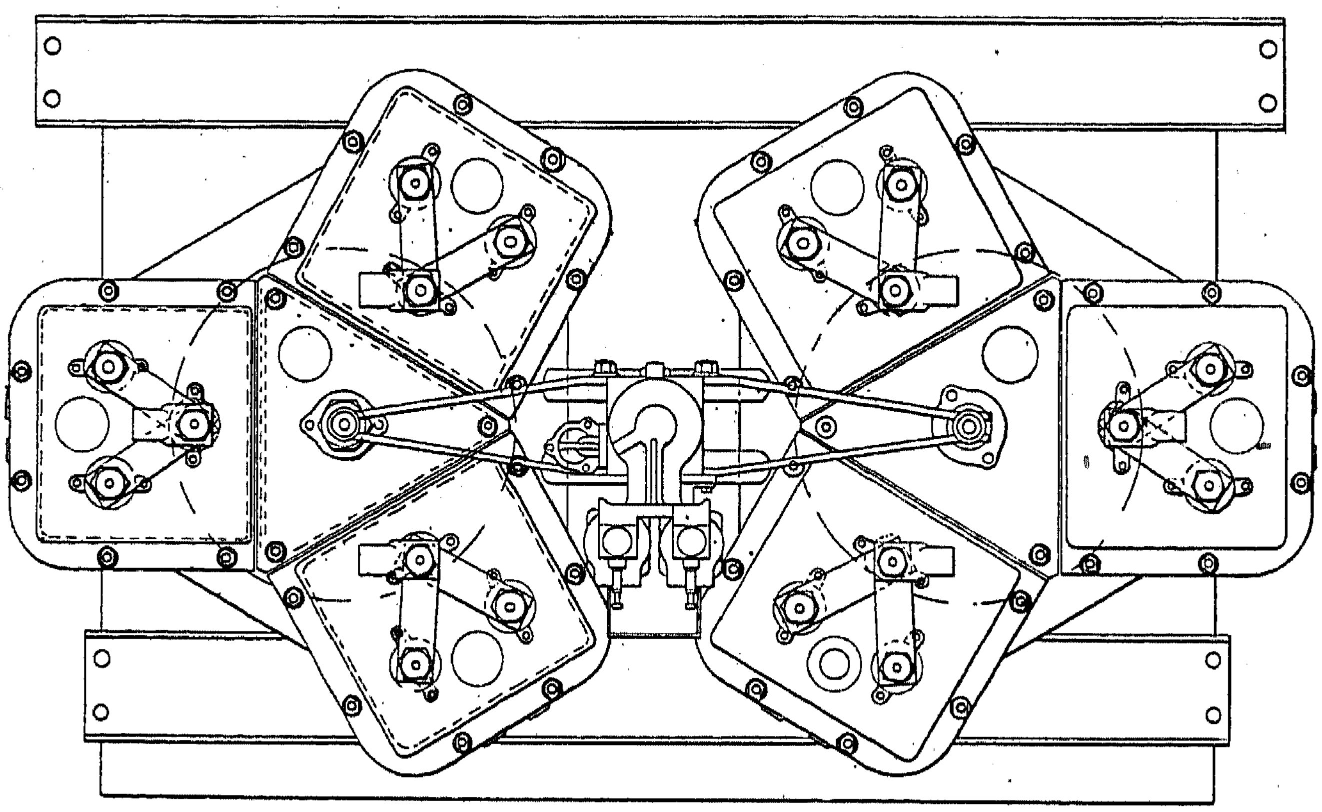


FIG. 4—SKETCH SHOWING HORIZONTAL ARRANGEMENT OF RHEOSTAT TANKS

per hr. and the "off" position, there is a notch which will give a 14-mi. (22.5-km.) per hr. combination on one truck only in each unit. This position is useful for handling a light engine, switching, or starting up a long train of empties. The other position is between the 14 and 28 mi. per hr. combination. This is for changing over from 14 to 28 mi. per hr. without losing tractive effort or causing sudden jolts in the train while changing over. The transition is made by first changing over one pair of motors in each unit to 28 mi. per hr., and as soon as the rheostat for these motors has reached the flush level position on the 28-mi. per hr. combination, the speed handle is moved to the full 28-mi. per hr. position, which will thus change over the remaining pair of motors.

The accelerating drum has three operating positions, marked

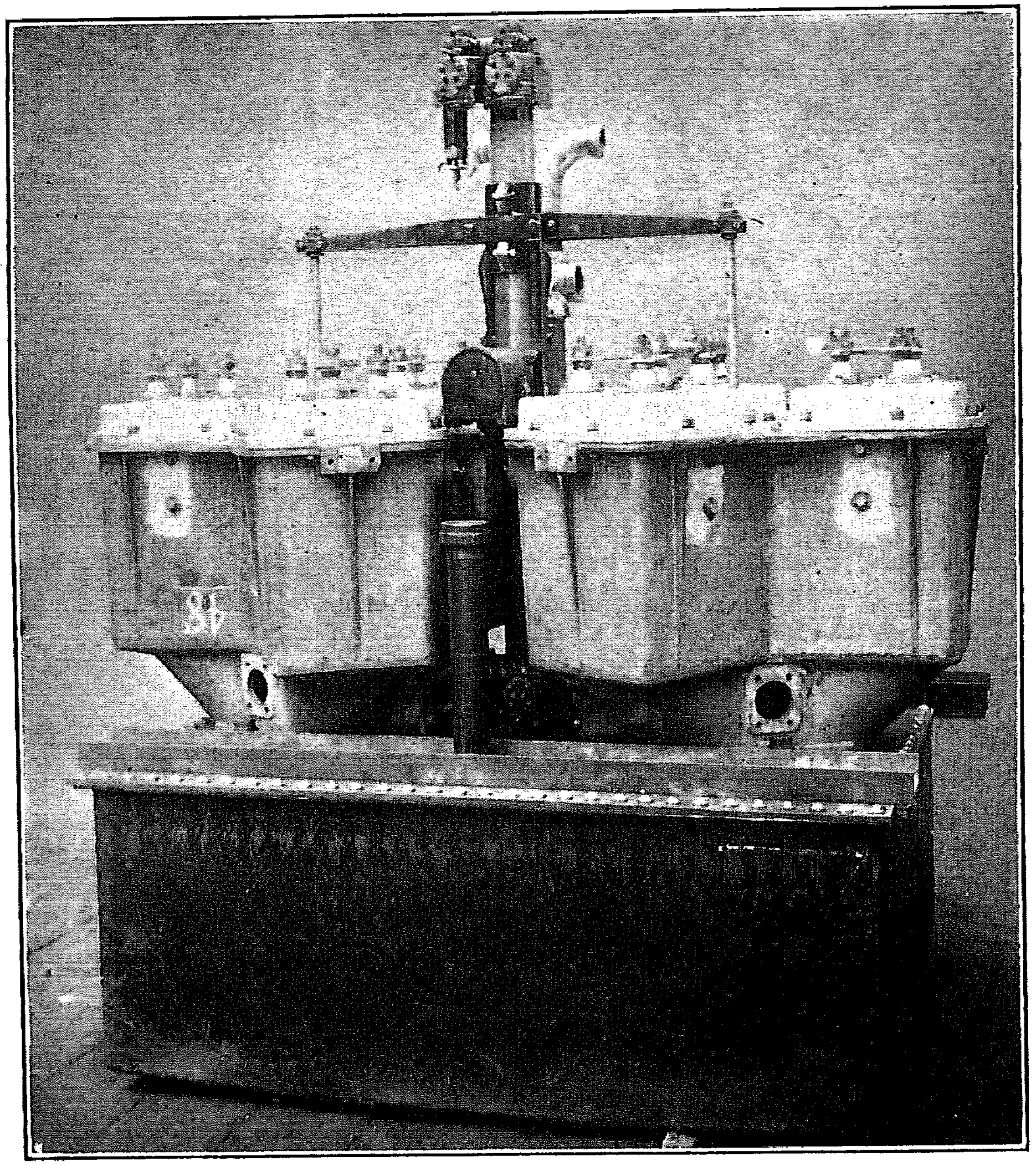
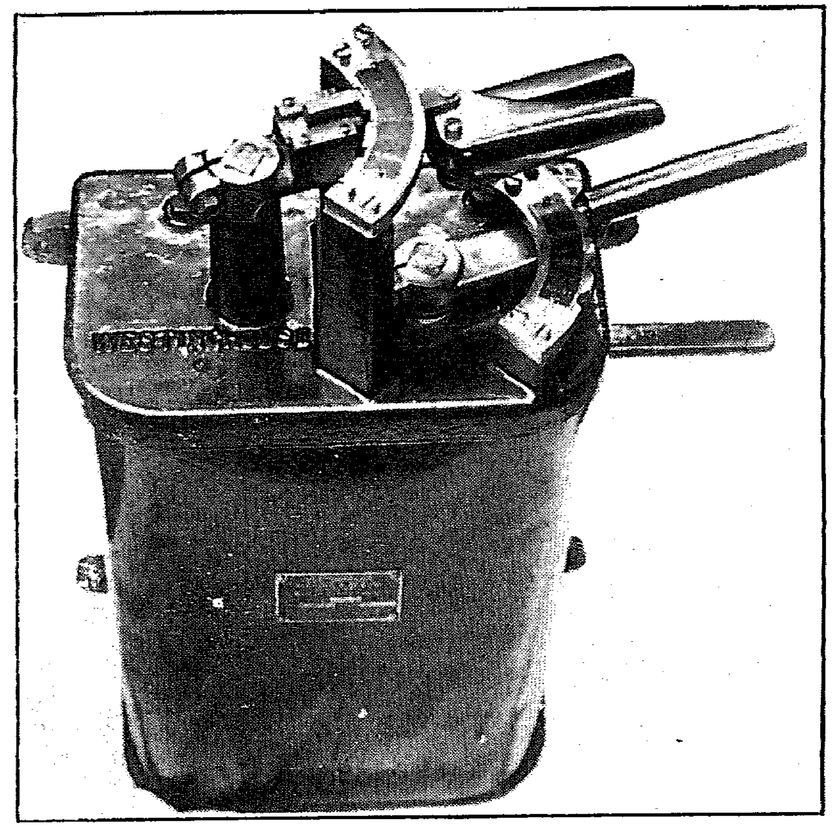


FIG. 2—THE LIQUID RHEOSTAT [HALL]



[HALL]
FIG. 5—THE MASTER CONTROLLER

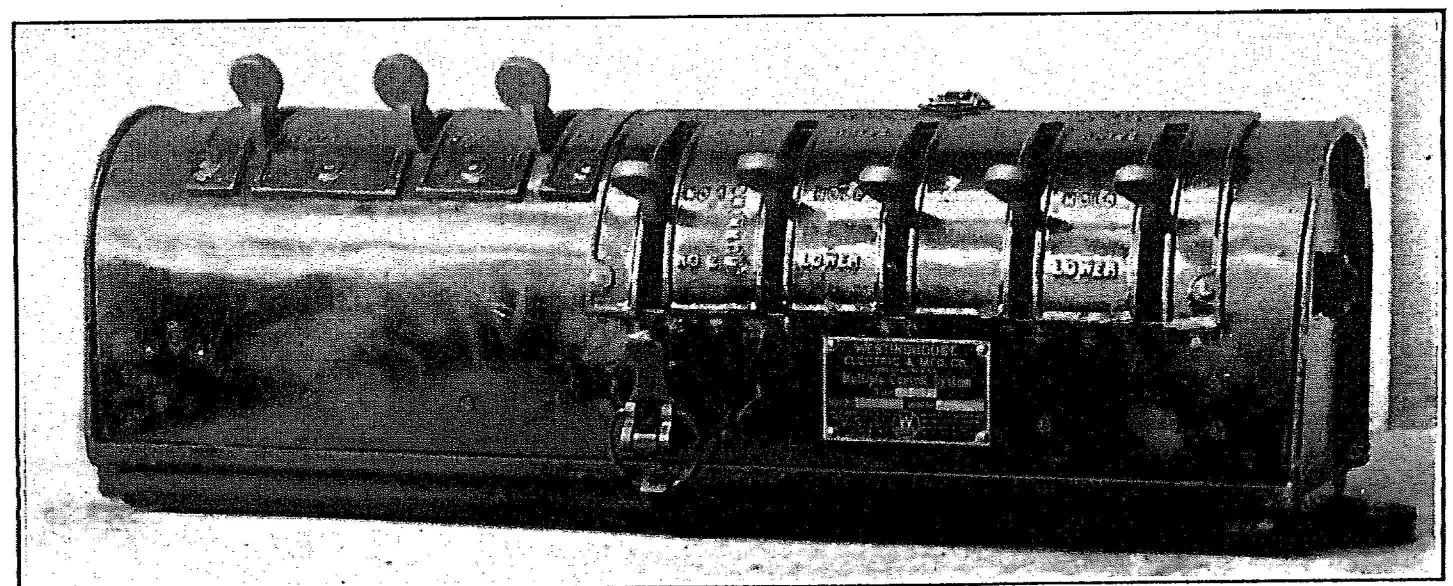


FIG. 6—AUXILIARY CONTROLLER [HALL]

"lower," "hold," and "raise." These terms refer to the level of the liquid in the rheostat.

In addition to the master controller, an auxiliary controller, Fig. 6, is provided, in which are located levers for the control of the pantagraph, phase converter, etc., and a set of levers by means of which the load on each pair of motors may be governed independently. This independent control is provided so that any difference of load between the various trucks may be corrected, such as that due to difference in wheel diameter, variation in electrolyte, etc. It is also advantageous in the event of one truck slipping its wheels. When this occurs, the torque on this truck can be reduced until the wheels again catch the rail. It can then readily be brought back to full torque without reducing the torque of the remaining drivers.

When the rheostats are full of liquid, the proper short-circuiting switches are closed, short-circuiting the motor secondaries. These short-circuiting switches do not come in until the operating mechanism is in the full "on" position.

Two limit switches are used, one for each speed combination, their function being similar to an overload trip, except that they do not open the main circuit. Should the torque exceed a predetermined amount, the limit switch will open the control circuit of the liquid rheostat operating mechanism, and thus lower the level of the electrolyte, inserting more resistance in the secondary of the motor. These limit switches are especially useful for preventing the motors on the rear locomotive from being overloaded when the train is being brought to a stop.

The cooling tower for electrolyte consists of a series of inclined trays, the liquid flowing over the trays while air is blown over the surface of the liquid to dissipate heat by vaporization. A supply pipe for the cooling tower is connected to the main circulating system near the outlet of the pump. This will by-pass a certain amount of liquid which, after flowing over the surface of the trays, flows back into the supply tank.

The cooling tower operates whenever the locomotive is in service; the rate of cooling varies according to the temperature of the liquid—the hotter the liquid, the more effective the cooling tower becomes.

The results obtained in this severe service, in flexibility of control, capacity and ability to withstand extraordinary duty, have demonstrated conclusively the advantage of this method of control.

DISCUSSION ON "THE LIQUID RHEOSTAT IN LOCOMOTIVE SERVICE" (HALL), NEW YORK, FEBRUARY 9, 1916.

C. D. Knight: The ordinary industrial liquid rheostat, Fig. 1, used considerably for mine hoisting work, consists of a large tank with a chamber at the top containing the electrodes and movable weir, controlled through a system of levers by the hoist operator. The position of this weir determines the level of the water.

An electrically operated pump having usually a capacity of about 300 gallons a minute pumps the electrolyte from the lower part of the tank to the upper chamber in a predetermined period, usually five to twelve seconds. When the weir is brought to its lowest position the upper chamber is emptied, the electrolyte dropping into the lower part of the tank, where its temperature is lowered by means of cooling coils.

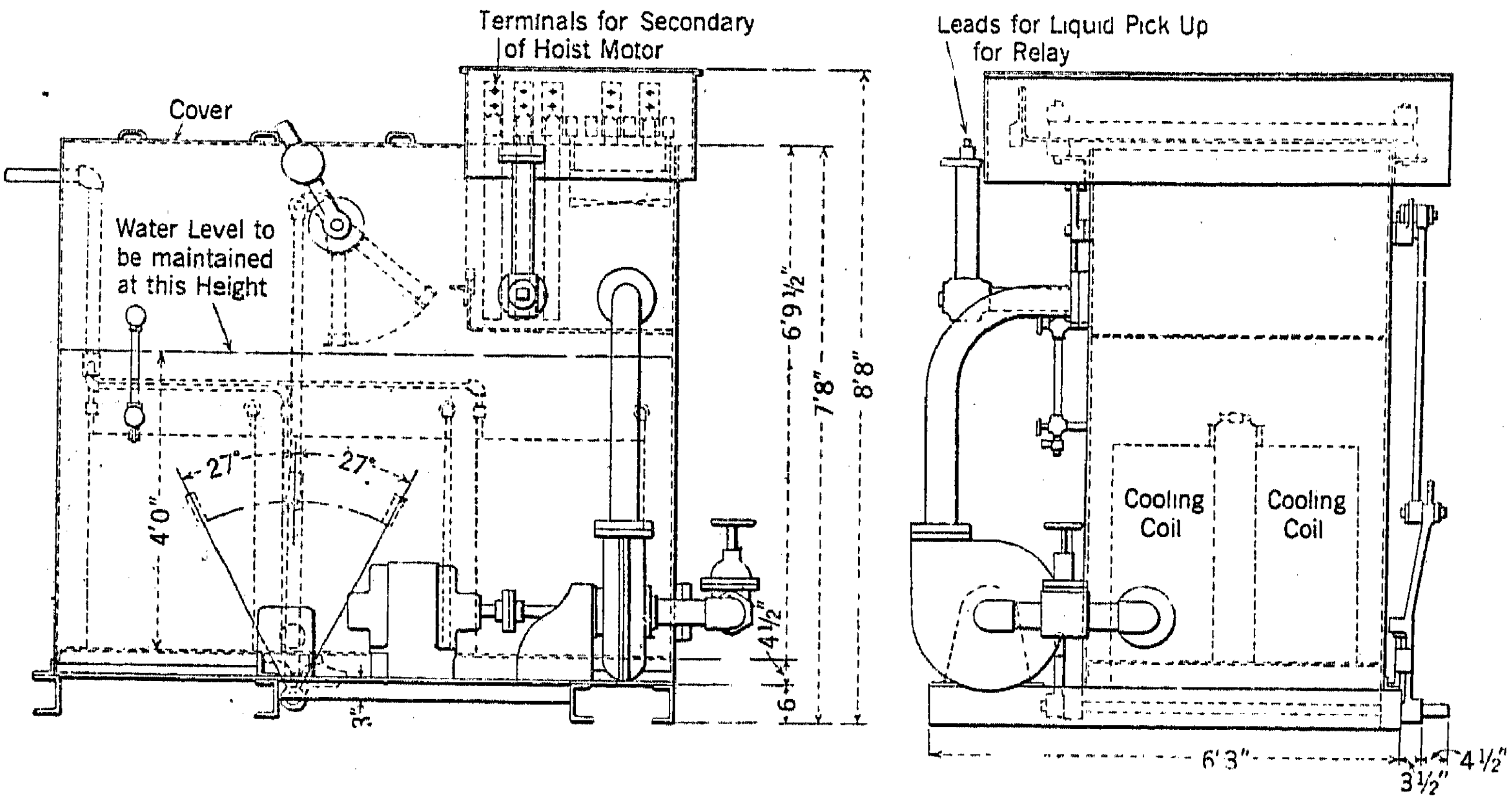


FIG. 1

Mr. Hall has told us that his method of cooling the electrolyte is by running it over a certain number of cooling trays. The capacity of a liquid rheostat depends to a great extent on the safe running temperature at which the electrolyte can be maintained. As Mr. Hall has shown us only the general construction and overall dimensions of his rheostat without any information regarding the cooling trays, I should like very much to have him give some further information with reference to the size and cooling capacity of the trays; also some information regarding the electrical characteristics of this rheostat. In other words, what amperes and volts can be carried for intermittent and continuous duty, as there are very few figures in the paper, which would go to show the actual capacity of the device.

The characteristics of induction motors require more or less resistance in the rotor circuit for relatively long periods, and considerable energy must be dissipated. How much does this

amount to, and how much water would be evaporated under operating conditions? He states that in this type of device you can use as much water as you please, bearing in mind that there is a big supply of water for cooling. I should like to know how he keeps a constant solution if he is continually evaporating the electrolyte and refilling the tank with fresh water.

Mr. Hall also states when the rheostats are full of liquid the proper switches are closed, short circuiting the motor secondaries, and that these short-circuiting switches do not come in until the operating mechanism is in the "full on" position. I wish to ask Mr. Hall if he has any interlocking arrangement, which insures that the motor secondaries are not short circuited during the accelerating period of the motor.

R. E. Hellmund: Mr. Knight asked how large the cooling tower for the water is. As far as I remember, each of the cooling towers in which the water runs down and the air goes up, is about four to five feet high, two to three feet wide, and two feet six deep. It is very small as compared with anything else that could be done. The reason, as mentioned in the paper, is that the water evaporates and heat is dissipated in that manner.

Regarding the capacity of the tower, I might say that at times the rheostat for one of the cooling towers takes care of 800 amperes with about 750 volts to start with during accelerations for periods of five or ten minutes, or even longer, and I have also seen it operate for periods of ten or fifteen minutes at one time; when the signals are against the train these loads are often repeated several times without causing trouble of any kind. The only difference that can be noticed under such severe conditions is that some steam comes out of the cooling tower exhaust.

As mentioned by Mr. Knight, the evaporation of the water will, as a matter of course, change the solution, but we find that the rheostat is not at all sensitive in that respect, and by adding a few gallons of water about once in twenty-four hours, it can easily be taken care of.

Mr. Knight asked if there was any interlocking system which assures that the short-circuiting switches do not come in until the water is at high level. There is such an interlocking system, consisting of contacts which are located at the top of the rheostat, and are closed by the water when it gets there. This insures the reliable operation of the rheostat.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER

BY G. M. EATON

ABSTRACT OF PAPER

The paper shows that chattering wheel slip is characteristic of all types of electric motive power. The application of the motive power in the electric and steam drives is compared, and the reasons for the chattering wheel slip and the means of measuring and rectifying the same are given.

WHEN THE steam pressure in the cylinders of steam motive power is high enough to start slipping of drive wheels, their acceleration is fairly uniform and rapid, the load on the piston being well sustained on account of late cut-off and stored steam in pipes, receivers, etc.

In contrast to this, with electric motive power, regardless of the method of transmitting the tractive effort from the rotors to the wheels, the acceleration after slipping starts is liable to be erratic, being dependent upon the distribution of rotating masses, and upon the characteristic of the coefficient of friction between wheel and rail.

The fundamental difference between the running gear of steam and electric motive power is that in the steam locomotive, the only moving parts having relatively high moment of inertia are the driving wheels.

In an electric locomotive, the moment of inertia of the rotors, especially when operating through a gear reduction, may be as great as or greater than that of the driving wheels.

The combined inertia of connecting rods, cross-heads, piston rods and pistons is practically negligible as far as it affects acceleration of driving wheels after slipping starts. In an electric locomotive, when slipping occurs, the sequence of events is as follows, regardless of the type of drive:

Current is applied to the motor and the rotor starts to turn. Clearances in the entire transmission mechanism are first eliminated. Then, as the torque is increased, the metal of the

transmission, framing, etc., is bent and twisted, or otherwise deflected. This stressed metal becomes a storage battery of energy. Finally the tractive effort reaches a value sufficient to overcome the existing adhesion at the rail (coefficient of friction of repose), and the wheel starts to slip. The instant relative movement occurs between wheel and rail, the coefficient of friction drops from that of repose to that of relative motion. There is, therefore, an opportunity for the stressed metal to start discharging its stored energy, since part of the resisting force has disappeared. This energy is expended in accelerating the wheels ahead of the angular position they occupied relative to the rotor at the instant slipping started.

It is necessary next to analyze independently the two divisions of the rotating system, namely, rotors and wheels.

Since the wheels are being accelerated ahead of the rotors, the rotors are losing their load and will tend to speed up. This is true not only of motors of series characteristic, but also of induction motors when running below synchronism, as will ordinarily be the case in traction work when the wheels slip. In fact, the induction motors, because their generated counter e. m. f. with increased speed is less than with series motors, will hold up their torque better and, therefore, accelerate faster. The induction motor, in this particular, more nearly approaches the steam locomotive, in which, at starting, steam is cut off as late as possible in the stroke, so as to get the maximum starting tractive effort.

Analyzing next the other division of the system, the adhesion at the rail will decrease as the velocity of the wheel tread relative to the rail, increases. The effort being transmitted through the transmission system, however, will decrease very rapidly, due to expenditure of stored energy, and as soon as this effort, which is tending to accelerate the wheels, becomes less than the adhesion at the rail, which is tending to retard the wheels, the wheels will evidently start to slow down.

There are, then, two sets of rotating masses mechanically coupled, the masses at one end of the system accelerating, and those at the other end, retarding. As soon as clearances in the transmission are taken up, there is liable to be a jolt on the mechanical system, accompanied by a recoil. This gives the setting for chattering action, and such action has been experienced in practically every type of electrically-driven rolling stock where the motors are sufficiently powerful to slip the wheels at high adhesion.

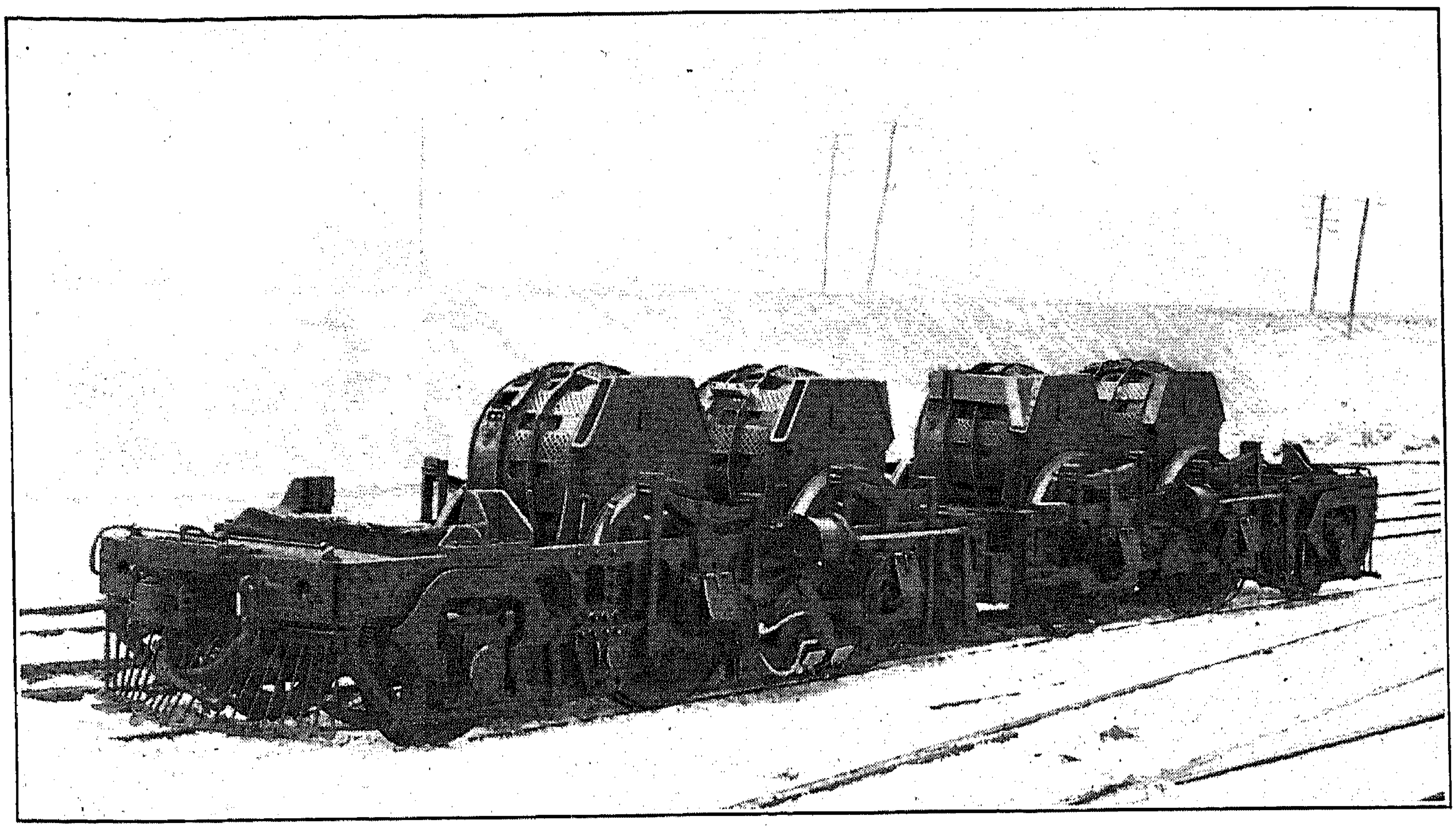


FIG. 1 [EATON]

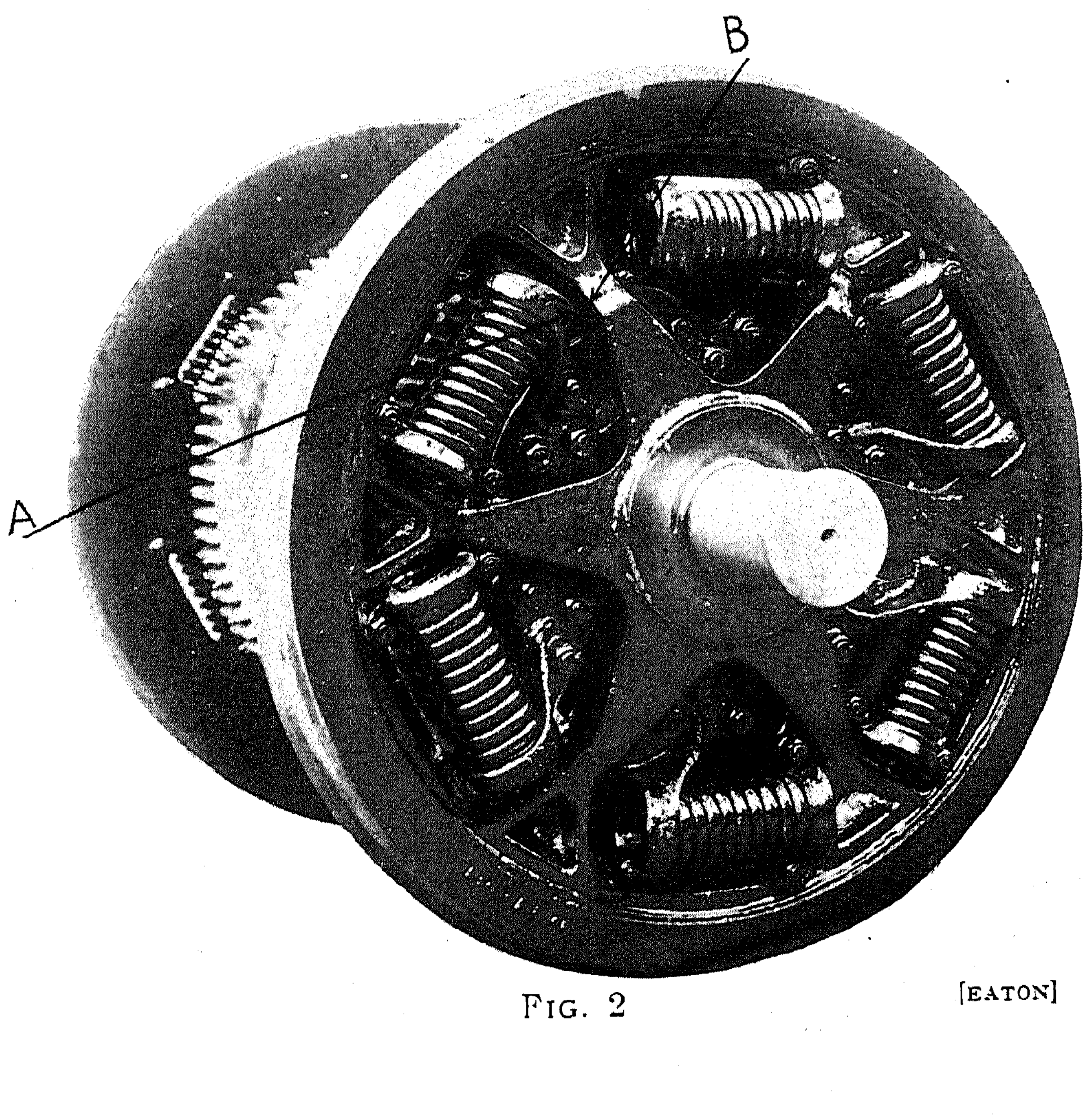


FIG. 2 [EATON]

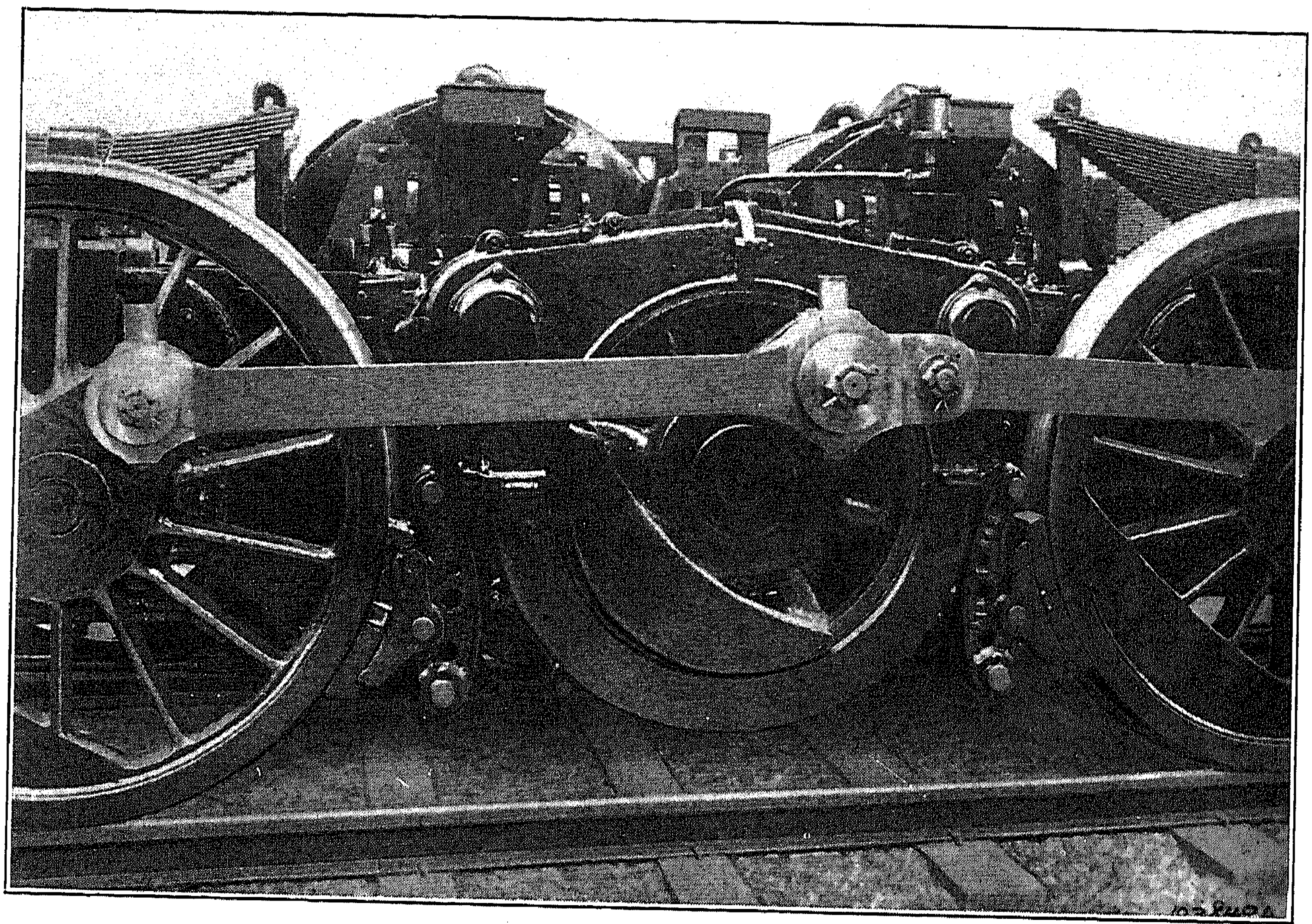


FIG. 3 [EATON]

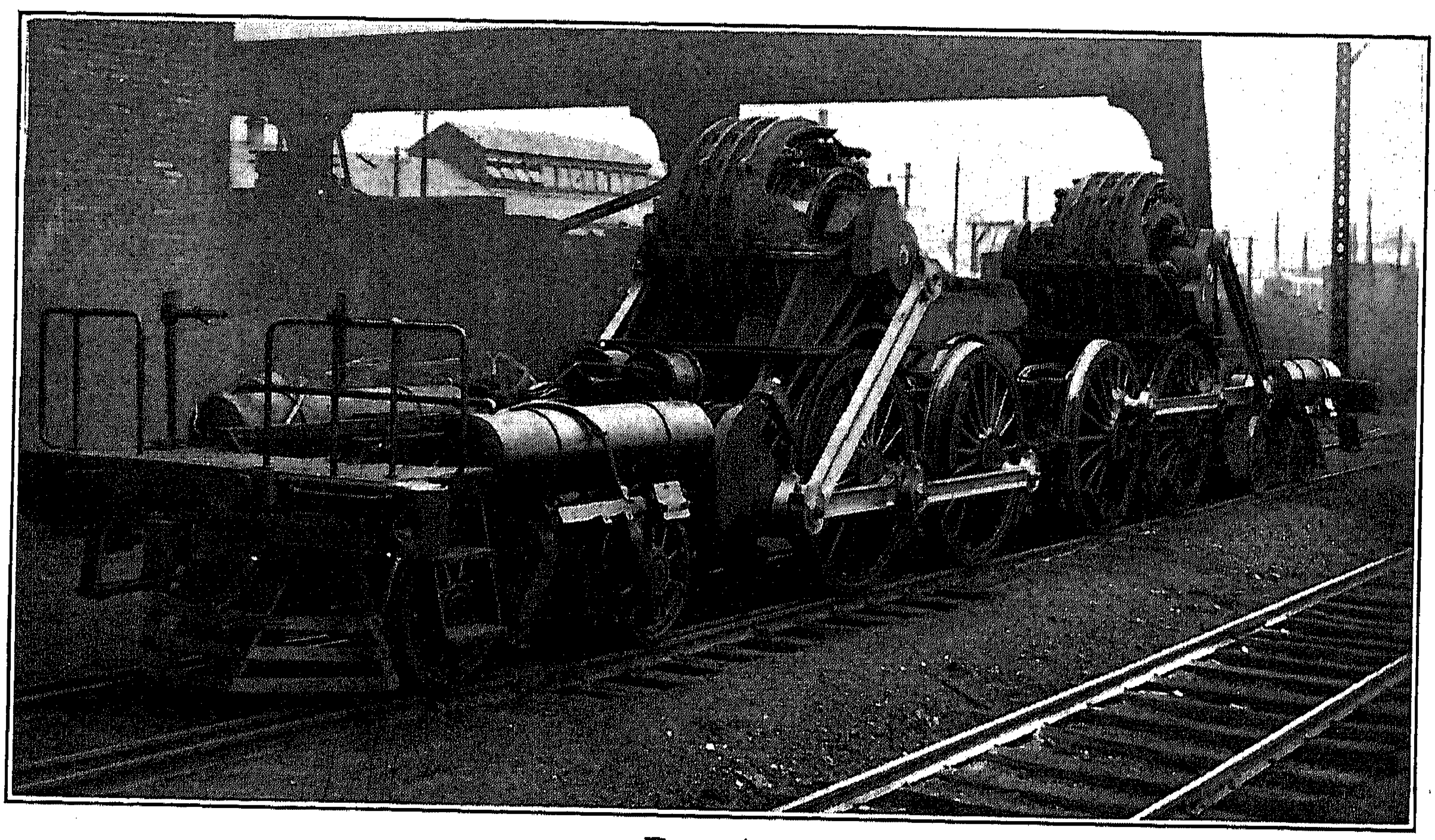


FIG. 4 [EATON]

This occurred on the geared freight and passenger locomotives whose transmission is shown in Fig. 1. The quill arms at the point marked *A* hit against the wheel spokes at the point marked *B*, Fig. 2, and more or less breakage of these arms occurred. It was found, however, that the arms which broke had blow-holes in the interior of the castings, and after these defective castings were eliminated, the breakage practically ceased.

In later locomotives in the same service equipped with two motors per axle, the change in armature inertia eliminated this striking. Chattering slip still occurred, but the capacity of the quill springs was sufficient to limit the amplitude of swing to a distance less than the existing clearances.

A certain amount of similar striking again occurred in some switching locomotives, but here again the parts were strong enough to stand the service.

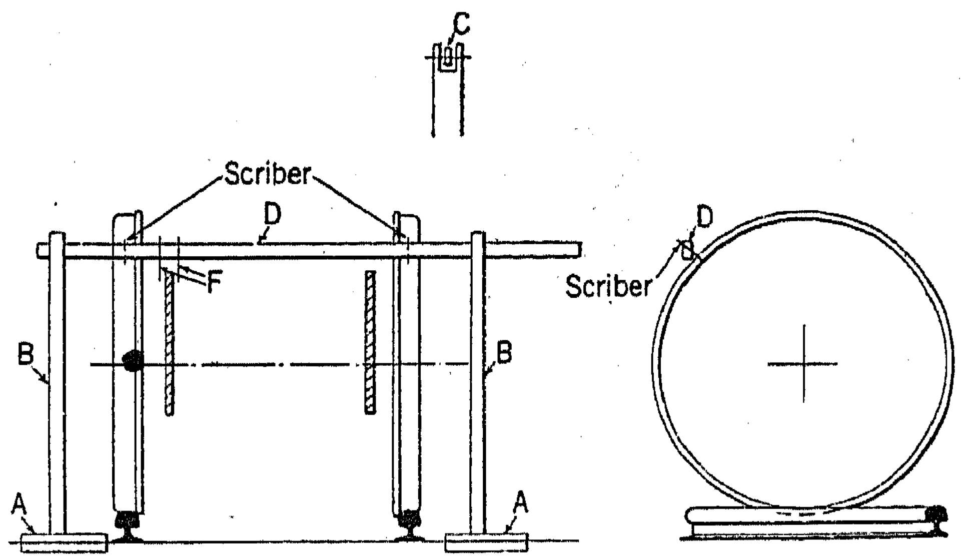


FIG. 5—HAND-OPERATED DEVICES FOR RECORDING CHATTERING SLIP

The same characteristic is occasionally observed in city and interurban cars, although this is much less frequent than in heavy hauling electric locomotives. This is due to the greater tractive power in proportion to the weight which is employed in the latter type of motive power.

In case of freight locomotives where the motors are geared directly to the axles the same phenomenon has been observed.

On the Norfolk and Western locomotives, chattering slip occurred in the running gear shown in Fig. 3. After the locomotives had been in service for some months, evidences of failure were detected in the crank pins. The cause was traced to chattering slip by means of a rough oscillograph, as shown in Fig. 5. The brakes were set on three trucks, and the oscillograph frame was set up on the fourth truck. The wheel tread was chalked. The oscillograph frame was oscillated about its sup-

porting points A, Fig. 5, the amplitude of oscillation being two inches. The time of complete oscillation was two seconds. The scribers were pressed against the wheel tread. The wheel treads were then slipped, and the characteristic diagram of the chattering slip was obtained, as shown in Fig. 6. The analysis in the figure is self-explanatory. By means of this diagram, it was possible to figure approximately the forces necessary to produce the acceleration and retardation which occurred, and the resultant stresses in the rods, pins, etc., were calculated.

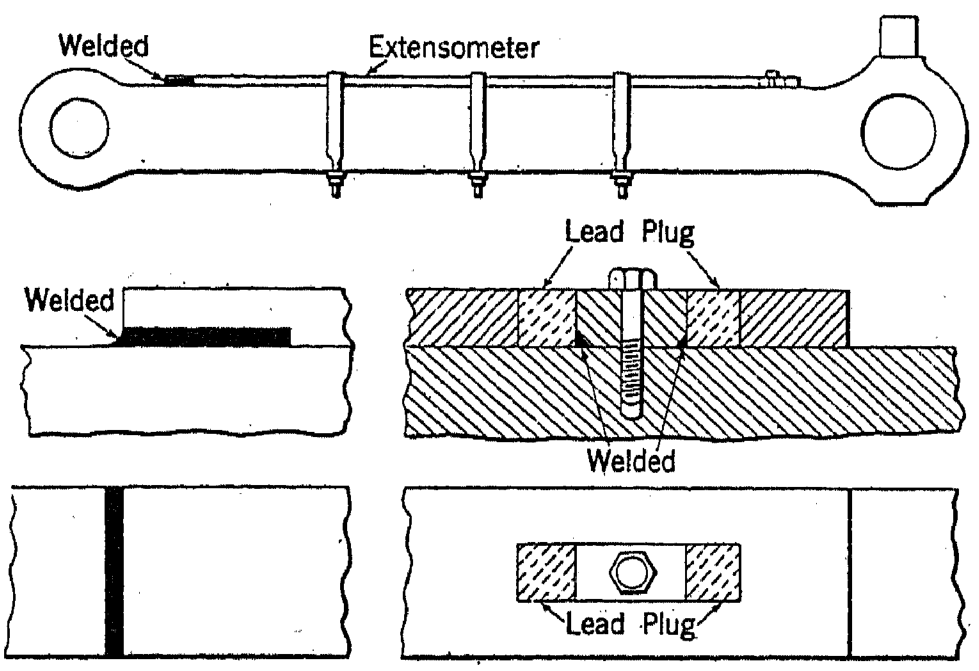


FIG. 7

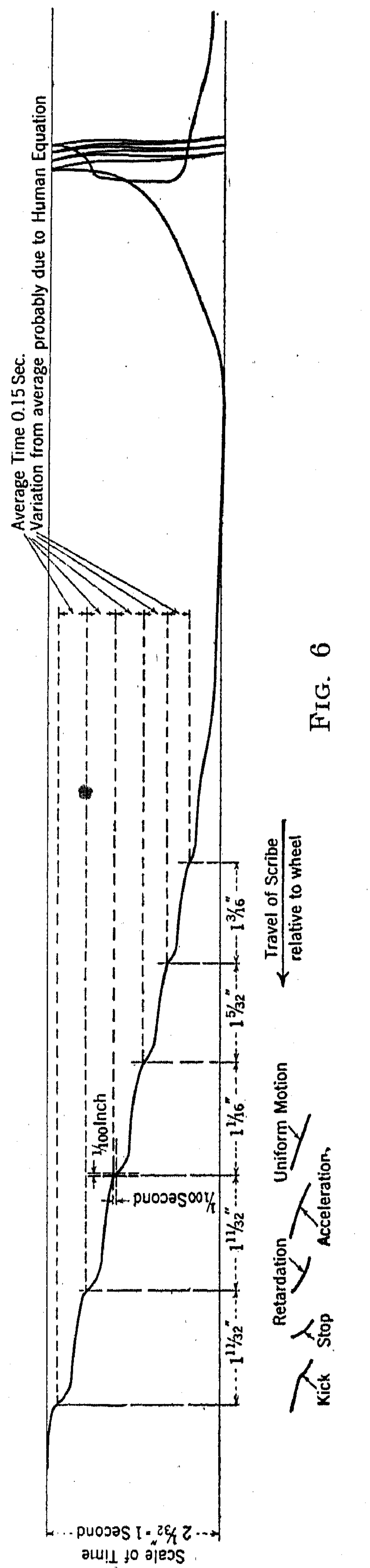


FIG. 6

To check the oscillograph figures, extensometers were arranged, as shown in Fig. 7, by means of which the connecting rods indicated their own stresses. The extension and compression of the rods were recorded by means of the compression of blocks of lead. This is evident from a little study of the figure.

The two methods checked within a very few per cent. On the basis of the results, new rods, pins, etc., were applied on the locomotives. These have proved adequate for the service.

This chattering slip was more evident on the Norfolk and Western locomotives than could have been anticipated, since this was the first time electric haulage had been

applied in service where such extremely high tractive efforts were required.

The phenomenon had never been observed on the locomotives with transmission as shown in Fig. 4. After it was experienced on the Norfolk and Western, however, permission was secured to make a test on the locomotives shown in Fig. 4. The wheels were slipped several times in succession in the same spot on the rails, and on the third slip, chattering occurred.

In all heavy hauling electric motive power, this problem must be considered, with every type of drive. The great number of variables entering and the wide fluctuation of certain of these variables render broad experience necessary in securing a successful solution of the problem. This has been gone into deeply and quantitatively by the writer and his associates, together with engineers of the locomotive works, with elaborate special testing apparatus, but it has been considered necessary to eliminate all quantitative values from this brief paper.

DISCUSSION ON " CHATTERING WHEEL SLIP IN ELECTRIC MOTIVE POWER " (EATON), NEW YORK, FEBRUARY 9, 1916.

S. T. Dodd: It occurs to me that chattering wheel slip is exactly the same phenomenon which has been reported on a good many European side-rod locomotives. Of course, the European designers have had more experience than we have had in designing various types of side-rod locomotives, and there have been reported in the foreign technical press several failures of this type of locomotive. I have in mind principally a couple of reports in German papers in regard to the Loetchberg locomotives. These locomotives, as you will remember, have characteristics which would increase the possibility of such a thing occurring. They have two very large motors of about 1300 h.p. each, geared to jack shafts the jack shafts tied together by Scotch yokes, which in turn are connected to the driving axles by side rods. In the papers I have in mind, they describe the disturbance in these locomotives, as a " shuddering " motion occurring at speeds of 20 to 25 miles an hour. This is so intense as to break the cranks and the Scotch yokes, sometimes by tearing them apart by tension, and sometimes crushing them by compression. The papers I have made reference to discuss mathematically the motions and the stresses which occur in such a frame work as that, showing that these forces are proably due to the building up of mechanical resonance between the springing of the driving rod on one side, and the inertia of the very heavy armatures on the other.

As far as I can see, that is what Mr. Eaton describes in his paper, in clear physical language, where the German writers describe it mathematically. The cure which the mathematical analysis pointed out was the introduction of springs of considerable amplitude of motion as compared with the amount of displacement you would ordinarily get in the side rods. By inserting springs whose amplitude of motion could be measured in inches rather than in thousandths of an inch, they expected to eradicate these troubles. For the Loetchburg locomotives, spring gears were ordered sometime before the European war, but I have never heard that they were installed, or the results if they were installed.

The question which occurs to me is whether Mr. Eaton's chattering wheel slip is not another phase of exactly the same phenomena which appeared on the Loetchburg road and on many of the European locomotives, and whether a cure for it would not be found in exactly the same thing which was found as a cure for the European locomotives, that is, the introduction of a certain amount of spring, with a certain amplitude of motion and, with a dead beat action which would damp out these oscillations before they could build up to any considerable extent.

W. I. Slichter: About ten years ago I was called on to make some calculations as to the effect of the pulsating torque of single-

phase motors on the gears and transmission between the motors and wheels, and when I got my equation of friction, inertia and mass and elasticity of the material, I found I had an equation like that of a single-phase circuit, with resistance, inductance capacitance, and as soon as I had the equation I saw the solution—change the inductance or capacitance so you no longer have resonance, and the chattering would disappear.

Charles F. Scott: About six months ago Mr. Eaton was called down to the West Virginia mountains by telegraph to diagnose this difficulty described in the paper. He found that the wheels were slipping. His problem was to find out why they were slipping, and what to do to prevent it.

He had at hand for his investigation of this oscillation all the refinements of the railway repair shop for supplying his physical apparatus, and his own initiative and ingenuity for devising the means of proceeding with the facilities at hand. The oscillations were scratched on a long strip of iron about 1/32 of an inch thick, and three or four inches wide, attached to the circumference of the driver. A sharp point was drawn across when the wheel began to slip. He had to try a good many times to get a record, and his actual record was a little scratch line on the rough piece of iron. Then taking that little wavy line, drawing tangents to it, getting the change in the rate of acceleration at different times and taking the moment of inertia of the wheel, he calculated the forces required for producing the recorded acceleration. Apparently, it was a very coarse, crude method.

Looking at that connecting rod, you would think if anything was solid and would stay together, it would be that great big steel rod. It is apparently quite a number of inches wide and several inches thick. He wanted to find out how much the rod was being stretched, and what was the variation in length of the rod during the slipping. That kind of measurement would ordinarily require microscopes, and other apparatus which a well equipped physical laboratory would afford. He proceeded to the repair shop and got a strip of iron and riveted it to the rod at one end—and attached it by a piece of lead at the other end. After this rod had gone through its vibration, he finds that the lead has changed a little in size, showing the amount of change of length between the great big side rod and the little constant length rod attached to it. Then from this elementary, simple method of measurement, he finds a very close agreement with the measurements made with scriber on the circumference of the driver.

W. L. Merrill: This same phenomenon has been known and has given trouble for years in ordinary metal cutting, that is, I refer to lathes, principally. Now, undoubtedly the tires of the locomotives we have been discussing here had the same trouble develop when they were being turned up, if too hard a cut was taken. The matter is not serious, except in some kinds of drive. For example, a punching press which is foot operated; that is,

a fly-wheel is running all the time and the clutch thrown by a lever, if the press is driven by an individual motor, and this motor is controlled by an automatic starter, which depends on current flowing through some part of the mechanism for holding home the controller or the starter in the full-on position. If we have a heavy cut to make with this press, upon the releasing of the load as the die travels through the stock, the twist or whatever you gentlemen choose to call it, that is put in the gearing mechanism at the time the fly-wheel is giving up its energy is immediately reversed the other way, and the current reverses through the motor, the motor shuts down and the machine stops. That is a simple matter and can be taken care of by putting on a type of starter which depends on voltage instead of current for holding it in position.

The same thing occurs on lathes, when driven through the back gear, and several sets of gearing between the point of application of power which may be a belt, if too heavy cuts are taken or the angle of the tool is ground improperly.

I mention that as being exactly the same thing as what we are discussing in the slippage of the wheels.

G. M. Eaton: Referring to Mr. Dodd's discussion, there is a point of inherent difference between the chattering which occurs at the time that the wheels are slipping, and the "shuddering" which Mr. Dodd refers to as having occured in various rod-connected European locomotives. This "shuddering" is a true synchronous action occurring at a certain critical speed, and at higher multiples of this critical speed. When this "shuddering" takes place on a given locomotive and at a given speed, it is of a practically uniform frequency. Contrasted with this, the chattering occurring when the wheels slip, may be over a surprisingly wide range of frequency. The writer has observed it, (at a frequency per second of $3\frac{1}{2}$, about 4, about 5, about 6, and up to as high as 33), on a given locomotive under conditions where the only observable difference was a probable variation in co-efficients of friction between the drive wheels and the rail.

This erratic action can be explained only by the presence of at least one very widely varying function, and this condition is met by the characteristics of friction between the rail and the drive wheel.

The illustration brought out by Mr. Merrill fits very much better. In a lathe, the action of the tool in producing the chip may cause alternate smooth running and breaking of the chip, and this will provide the necessary setting for production of vibration. There are two or three other actions which may occur and give the necessary conditions. Cuts of various depths will alter the frequency.

Chattering wheel slip has occurred in various locomotives where true resonance at high-speed running has never occurred, thus showing conclusively that the setting is different for the production of erratic chattering slip, and true resonance.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATTMETER CONNECTIONS

BY W. B. KOUWENHOVEN

ABSTRACT OF PAPER

The object of this paper is to describe a method of checking the correctness of the connections of a polyphase watt-hour meter on a three-phase circuit; and to show that the methods most commonly used for this purpose are unreliable. Polyphase wattmeters are classified according to the number of their voltage terminals and expressions giving the amount of energy theoretically registered by the meter are derived for all possible arrangements of the connections for each class. The correctness of these expressions was checked experimentally. The expressions are given in the form of tables. A study of these tables reveals the fact that the methods of checking the connections in most common use are unreliable. A method is developed which may be relied upon to check the correctness of the meter connections on a balanced three-phase circuit at any power factor. Rules are worked out from this method, that make the rectification of incorrect connections simple. In addition to this, another method is described which may be used on balanced or unbalanced three-phase circuits at any power factor, provided the opening of one phase at a time is permissible.

THIS PAPER describes a method for ascertaining the correctness of the connections of a polyphase wattmeter on a three-phase circuit.

The accurate measurement of electric power is very important, and on three-phase circuits polyphase wattmeters have come into general use for this purpose. The liability of making mistakes in the connections when installing these meters is well known and several methods of checking the connections are in use. Articles on this subject have appeared in the *Electric Journal** and in other publications, and the National Electric Light Association devotes several pages of its handbook to a description of methods for checking the connections. A canvass of some thirty power companies throughout the country brought out the fact that almost the only method of checking the connections in actual use is that of opening the voltage or current supply of each element of the meter in turn and noting the direc-

* See Bibliography at end of paper.

tion of rotation. This should be in the right direction if the power factor is above 0.5. However, not only is the above check unreliable, but also none of the other simple checks in use may be completely relied upon in identifying the correctness of the connections. It is possible for the meter to satisfy these checks and still be incorrectly connected. For this reason the writer undertook the study of the connections of a polyphase wattmeter.

A study of all the possible arrangements of the connections was made, and the direction and rate of rotation of the disk was determined theoretically for each arrangement. The theoretical results were also checked experimentally. A simple method of checking the correctness of the connections of a polyphase meter on a three-phase balanced circuit at any power factor was developed from the results.[1] The assumption of a balanced load is justified by the fact that every customer requiring a polyphase wattmeter has at least one three-phase motor. Although the discussion is confined to watt-hour meters, the results apply equally well to other similar meters.

The Investigation

It is a well-known fact that a polyphase watt-hour meter consists of two separate single-phase elements acting upon a common shaft. Each element is provided with separate current and usually separate voltage terminals, and for the purpose of this investigation the meters are classified according to the number of voltage terminals provided.

Class A contains those meters which have two voltage terminals for each voltage coil, or four voltage terminals in all. Meters of this class may be used with or without voltage transformers.

Class B contains those meters which have but three voltage terminals. On these meters the ends of the voltage coils that are at the same potential are connected together and brought out to a common terminal. This class of meters may also be used with or without voltage transformers.

Often in practise, especially when potential transformers are used, the two voltage terminals of a Class A meter that are at the same potential are connected together. In such cases meters

1. After the completion of the paper the writer learned that the method developed is not new. However, no mention of it was found in technical publications.

with four voltage terminals belong to the Class B type of instruments.

Class C contains those meters which have but one voltage terminal. This terminal is the common terminal referred to in Class B. In Class C meters, the other end of each voltage coil is connected to one end of the corresponding current coil and brought out to a single terminal. Meters belonging to this class are seldom used with either voltage or current transformers and are usually of the house type.

The number of possible arrangements of the connections is different for each class and therefore each class was considered separately. The number of different arrangements of the voltage connections is given by the expression

$$y = \underline{/x}$$

where x is the number of voltage terminals of the meter and y the number of different arrangements of the connections to these terminals possible. For each arrangement of the voltage terminals, there are sixteen arrangements or combinations that may be formed by the current connections and by the opening of the voltage leads. These are as follows:

(a) Phase I and phase II connected correctly
(b) Phase I reversed, phase II correct
(c) Phase I correct, phase II reversed
(d) Phase I and phase II reversed
(e) Phase I and phase II correct, voltage lead 1 open
(f) Phase I and phase II correct, voltage lead 2 open
(g) Phase I and phase II correct, voltage lead 3 open
(h) Phase I reversed, phase II correct, voltage lead 1 open
(i) Phase I reversed, phase II correct, voltage lead 2 open
(j) Phase I reversed, phase II correct, voltage lead 3 open
(k) Phase I correct, phase II reversed, voltage lead 1 open
(l) Phase I correct, phase II reversed, voltage lead 2 open
(m) Phase I correct, phase II reversed, voltage lead 3 open
(n) Phase I and phase II reversed, voltage lead 1 open
(o) Phase I and phase II reversed voltage lead 2 open
(p) Phase I and phase II reversed, voltage lead 3 open

The presence or absence of current transformers does not in any way affect the number of arrangements of connections. However, this is not true of voltage transformers; and where their presence introduces additional arrangements of connections, their action was studied.

Class A Meters

The correct connections of the Class A type of polyphase meter when used without voltage transformers is shown in Fig. 1.

Phases I and II of the three-phase line contain the current transformers which supply current to the current coils I and II of the meter, respectively.

(In all of the figures used in this paper, the current coils are placed horizontally and numbered with the Roman numerals I and II. The voltage coils are placed at right angles to the current coils, and their terminals are numbered according to the three-phase line to which they are connected.)

The number of possible arrangements of the voltage connections to the four meter terminals are in this case given by the expression

$$y = \frac{|\underline{x}}{|\underline{2}}$$

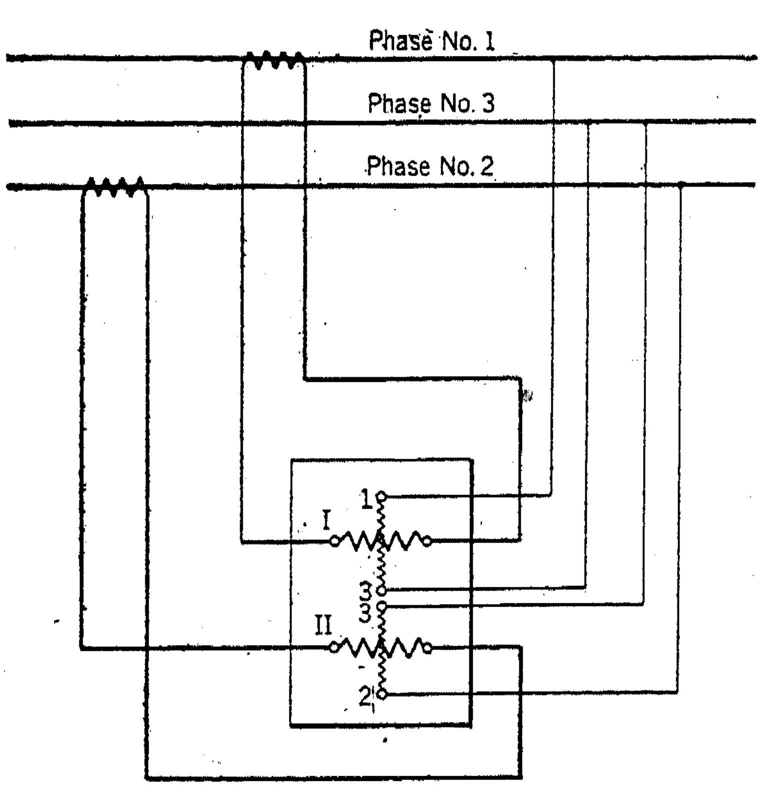


FIG. 1

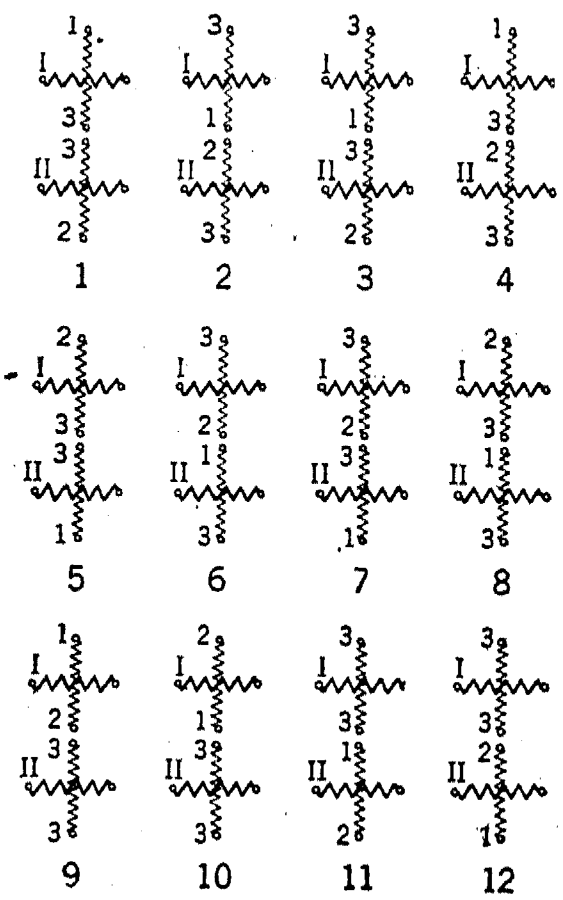


FIG. 2

as two of the voltage terminals are connected to the same phase. Substituting the value of x we find that there are 12 possible arrangements of the connections. These are shown diagrammatically in Fig. 2.

There are also 24 additional arrangements of the voltage connections possible. Twelve of these are formed by connecting two of the meter terminals to phase 1, one terminal to phase 2, and one to phase 3; the other twelve are formed by connecting two meter terminals to phase 2, and to phase 1, and one to phase 3. All of these arrangements are incorrect. They are treated in Tables VIII and IX.

The first eight of these arrangements, Fig. 2, illustrate not only the correct connections, but also mistakes that are more or less commonly made. Wrong connections as illustrated by the last four arrangements of connections are practically impossible except in meters where the terminals belonging to each element are not readily identified. Such connections are just as improbable as the connections of the leads of a current transformer to the terminals of the different current coils. They have been included in this investigation only for the sake of completeness, and to prove that mistakes of this character may be eliminated by the method that will be outlined for the checking of connections.

As each arrangement of voltage connections has 16 possible arrangements or combinations of the connections of the current coils, and opening the voltage leads, we have a total of 192 theoretically different possible connections for this class of meter when used without voltage transformers.

CALCULATION OF THE THEORETICAL EXPRESSIONS

In order to study the effect of any one of the 192 connections upon the operation of the meter it was necessary to derive the theoretical expression for each case, from which the rate of rotation of the disk could be calculated for any load. The following examples serve to illustrate the method followed and the meaning of the expressions found.

Let P = the reading of the polyphase watt-hour meter.

E = the line voltage

E_1, E_2, E_3, I_1, I_2 and I_3, represent the phase voltages and currents respectively.

Φ_1, Φ_2 and Φ_3 represent the phase angles respectively. For the purpose of calculations we shall assume a balanced load with lagging power factor, and that the system is star-connected. Then we have

$$E_1 = E_2, = E_3,$$
$$E_{1,3} = E_{2,3} = E_{1,2} = E$$
$$I_1 = I_2, = I_3, = I$$
$$\text{and } \Phi_1 = \Phi_2, = \Phi_3, = \Phi$$

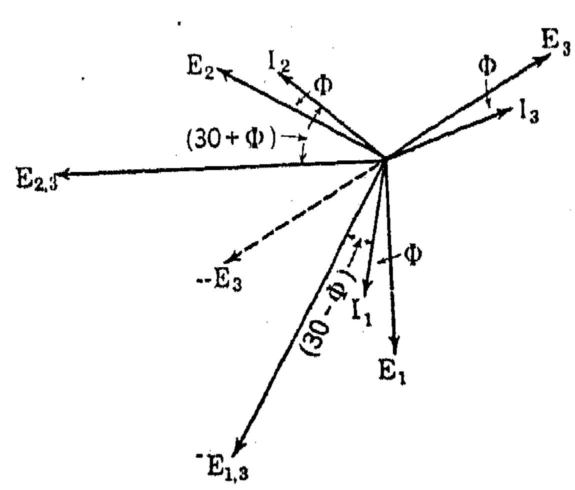


FIG. 3

The power of the circuit is given by the expression $(+\sqrt{3}\cos\Phi)\, I E$.

Calculation of the Value of P for the Case 1 (*a*);

Phase I and II Correct.

The meter is connected as in Fig. 1 and the vector diagram of the circuit is shown in Fig. 3.

Now,

$$P = I_1 E_{1,3} \cos (30 - \Phi) + I_2 E_{2,3} \cos (30 + \Phi)$$

$$= I E \left(\frac{\sqrt{3}}{2} \cos \Phi + \frac{1}{2} \sin \Phi\right)$$

$$+ I E \left(\frac{\sqrt{3}}{2} \cos \Phi - \frac{1}{2} \sin \Phi\right)$$

We find that $P = (+ \sqrt{3} \cos \Phi) I E$

The value of P equals the actual power of the circuit and therefore the connections, case 1 (a), are correct and the meter registers correctly the power consumed. It must be kept in mind that the use of the term correct applies to the connections only and not to the calibration of the instrument.

Case 1 (b) *Phase I Reversed, Phase II Correct.*

We have now for P the expression

$$P = - I_1 E_{1,3} \cos (30 - \Phi) + I_2 E_{2,3} \cos (30 + \Phi)$$

$$P = (- \sin \Phi) I E$$

The meter does not register correctly and will run in the wrong direction with lagging currents. At unity power factor it will not run. The connections are therefore incorrect.

Case 1 (c) *Phase I Correct, Phase II Reversed.*

We find that $P = (+ \sin \Phi) I E$

The meter will run in the right direction but not at the correct speed. The connections are therefore incorrect. At unity power factor the meter will not register.

Case 1 (d) *Phase I and Phase II Reversed.*

We find $P = (- \sqrt{3} \cos \Phi) I E$

The meter runs in the wrong direction and therefore the connections are at fault.

Case 1 (e) *Phase I and Phase II Correct, Voltage Lead* 1 *Open.*
For this we get

$$P = \left(+ \frac{\sqrt{3}}{2} \cos \Phi - \frac{1}{2} \sin \Phi\right) I E$$

The direction of rotation will change from right to wrong when the power factor changes from values above 0.5 to values below 0.5. The connections are incorrect.

Case 1 (f) *Phase I and Phase II Correct, Voltage Lead 2 Open.*
P becomes

$$P = \left(+\frac{\sqrt{3}}{2}\cos\Phi + \frac{1}{2}\sin\Phi\right) I\,E$$

The meter runs in the right direction, but does not register correctly.

Case 1 (g) *Phase I and Phase II Correct, Voltage Lead 3 Open.*

For this case the value of P is indefinite. It may have the same value as 1 (e) or 1 (f) depending upon which of the leads 3 is open; or it may equal zero if both of them are open simultaneously. Therefore this case does not exist as a special case for this type of meter.

The above examples of the derivation of the theoretical expressions for P, with the addition of cases 2 (d), 6 (a) and 9 (a), will serve fully to illustrate the method of derivation.

Case 2 (d) *Phase I and Phase II Reversed.*

We find that

$$P = -\,I_1\,E_{3,1}\cos\{\pi - (30 - \Phi)\} - I_2\,E_{3,2}\cos\{\pi - (30 + \Phi)\}$$

$$P = (+\sqrt{3}\cos\Phi)\,I\,E$$

The meter will run in the right direction and register correctly the power, therefore the connections of case 2 (d) are correct.

Case 6 (a) *Phase I and Phase II correct.*

The vector diagram for this arrangement of connections is given in Fig. 4.

$$P = I_1\,E_{3,2}\cos(90 + \Phi) + I_2\,E_{3,1}\cos(90 - \Phi)$$
$$P = 0$$

The meter will not rotate and the connections are incorrect.

Case 9 (a) *Phase I and Phase II Correct.*

$$P = I_1\,E_{1,2}\cos(30 + \Phi) + 0$$

$$P = \left(+\frac{\sqrt{3}}{2}\cos\Phi - \frac{1}{2}\sin\Phi\right) I\,E$$

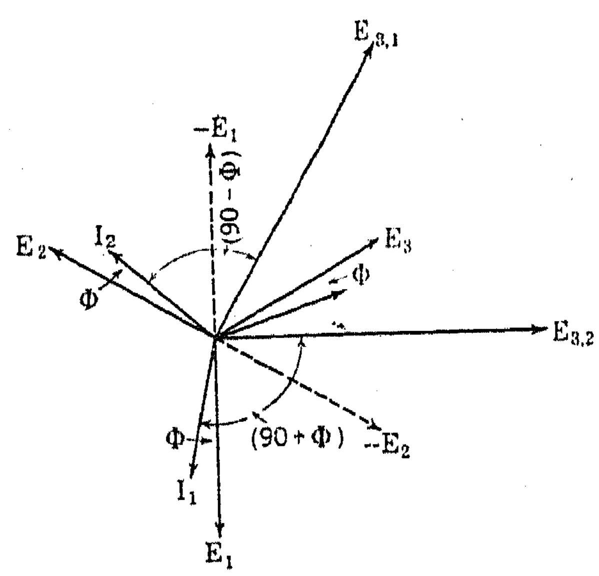


FIG. 4

The theoretical value of P for each one of the cases is given in Table II. The expressions are given in brackets and in every case the common term $I\,E$ has been omitted from the table.

Due to the fact that cases (g), (j), (m) and (p) are considered as non-existent, we have only 144 different cases or arrangements of connections for class A meters.

Experimental Verification of the Formulas

The correctness of the formulas was checked experimentally. The connections of a polyphase watt-hour meter were arranged in all of the possible combinations, and for each arrangement or case, the time of one revolution was determined at several different loads and power factors. The theoretical time was calculated from the derived expression for the given case, and the measured and theoretical results were compared.

The load consisted of a three-phase synchronous converter. The power factor was varied by changing the field excitation and was determined from ammeter, voltmeter and wattmeter readings and was also checked by means of a polyphase power factor meter. Due to changes in the line voltage and to other factors the load could not be maintained exactly constant, and an exact check between measured and calculated results was therefore not always possible.

As the time of one revolution is inversely proportional to the load, we have the relation

$$\frac{\text{Time of one revolution, Case.....}}{\text{Time of one revolution, Case 1 (a)}} = \frac{\text{Expression for Case 1 (a)}}{\text{Expression for Case.....}}$$

For each load and power factor, the time of one revolution in seconds was measured with the meter connected correctly. This time was called the reference time and was frequently checked. As soon as the reference time was found, the connections were changed to those of the case under consideration and the time of one revolution at the given load and power factor measured. The theoretical time for the given case was then calculated from the above relation and compared with the measured time. In Table I are to be found the results of the tests made for cases 1 (a) to 1 (k) for three different loads at different values of the power factor, which was in all cases lagging.

As has already been stated, Table II contains the expressions found for P for each of the 144 cases. These expressions were calculated under the assumption that the current was lagging. However, in order to adapt the expressions for use in instances where the current is leading, all that is necessary is to multiply

TABLE I

Case	Expression	Run 1. Power Factor = 1.0 Time of 1 rev. at this load, meter connected correctly = 14.4 sec.				Run 2. Power factor = 0.81 Time of 1 rev. at this load, meter connected correctly = 13.0 sec.				Run 3. Power factor = 0.42 Time of 1 rev. at this load, meter connected correctly = 12.2 sec.			
		Direction of Rotation		Time of 1 rev. sec.		Direction of Rotation		Time of 1 rev. sec.		Direction of Rotation.		Time of 1 rev. sec.	
		Theor.	Actual	Theor.	Meas.	Theor.	Actual	Theor.	Meas.	Theor.	Actual	Theor.	Meas.
1 (a)	$(+\sqrt{3}\cos\Phi)$	Right	Right	14.4	14.4	Right	Right	13.0	13.0	Right	Right	12.2	12.2
1 (b)	$(-\sin\Phi)$	None	None	∞	∞	Wrong	Wrong	31.6	32.4	Wrong	Wrong	9.8	9.8
1 (c)	$(+\sin\Phi)$	"	"	"	"	Right	Right	31.6	30.4	Right	Right	9.8	9.7
1 (d)	$(-\sqrt{3}\cos\Phi)$	Wrong	Wrong	14.4	14.5	Wrong	Wrong	13.0	12.2	Wrong	Wrong	12.2	12.2
1 (e)	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	Right	Right	28.8	29.2	Right	Right	44.5	48.	Wrong	Wrong	99.	100.
1 (f)	$(+\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$	"	"	28.8	30.2	"	"	18.4	18.2	Right	Right	10.8	10.8
1 (h)	$(+\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	"	"	28.8	28.8	"	"	44.5	47.6	Wrong	Wrong	99	102.
1 (i)	$(-\frac{1}{2}\sqrt{3}\cos\Phi-\frac{1}{2}\sin\Phi)$	Wrong	Wrong	28.8	30.0	Wrong	Wrong	18.4	18.4	"	"	10.8	10.8
1 (k)	$(-\frac{1}{2}\sqrt{3}\cos\Phi+\frac{1}{2}\sin\Phi)$	"	"	28.8	29.0	"	"	44.5	48.0	Right	Right	99	103.5

the sine terms by (— 1). The table also gives the direction of rotation of the disk for four different values of lagging power factor with each arrangement of connections. By the use of the table it is also possible in cases where incorrect or open connections are found, to determine from the meter readings, when the conditions of the circuit are known, the actual kilowatt-hours that have been used.

Checking the Connections

From Table II we see that there are 64 cases or arrangements of connections where the meter will run in the right direction at some value of the power factor between unity and zero lagging. Forty of these 64 occur on open circuits and 24 when all circuits are intact. As all meters and instrument transformers are tested for open circuits before they are installed, these 24 cases are the important ones. We must therefore consider the problem of ascertaining some simple means for the identification of the correct connections among the 24 arrangements. We also learn from the table that there are four arrangements of connections which give correctly the power passing through the meter. These four correct arrangements of connections are 1 (a), 2 (d), 3 (b) and 4 (c).

One of the most common methods in use for checking the correctness of the connections has been to open the current or voltage supply of first one element and then the other, noting the direction of rotation in each case. For power factors above 0.5 this should give rotation in the right direction for either element, and for below that value, in the right direction for one element and in the wrong direction for the other. A study of Table II shows that this is true for the four correct cases 1 (a), 2 (d), 3 (b) and 4 (c), and that at unity power factor it serves to eliminate all incorrect connections. Further study, however, shows that for power factors above 0.5 and below unity there are four other cases, 5 (c), 6 (b), 7 (d) and 8 (a), which also give continued rotation in the right direction when the voltage supply to either element is opened, and also that at 0.5 power factor there are four incorrect connections, namely, 1 (c), 2 (b), 3 (d) and 4 (c), which give the same indications when the voltage supply is opened, as the correct connections. We also find that the test may be relied upon for power factor below 0.5. A knowledge of the power factor is essential for its application.

New Method of Checking Connections

The method that the writer proposes for the checking of the correctness of the connections, is the interchange of voltage leads 1 and 2. Then if the original connections were correct, the rotation of the meter disk will cease at any value of the power factor (leading or lagging) on a balanced circuit. If the original connections were not correct, rotation in one direction or the other will take place after the interchange has been made. The proof of this is as follows:

Unity Power Factor. At unity power factor we find that for 12 cases the meter will run in the right direction with all the circuits intact. These are as follows: 1 (a), 2 (d), 3 (b), 4 (c), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c) and 12 (d).

The effect of the interchange of voltage leads 1 and 2 is given in Table III. Table III and also Tables IV, V, VI and VII are derived from the values given in Table II. We note in Table III, that when the voltage leads 1 and 2 are interchanged, the rotation of the disk will cease for the four correct connections, and that in all of the other cases it will run in the wrong direction.

Power Factor <1.0 *and* >0.5 *lagging.* Under these conditions we find 20 cases where the meter will run in the right direction with all circuits intact. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c), 2 (b), 3 (d), 4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c) and 12 (d).

The effect of the interchange of voltage connections on these cases is given in Table IV. From the table we see that, when the voltage connections are interchanged, the meter will stop for the four correct cases only, and for all other connections the meter will run either forward or backward.

Power Factor $= 0.5$ *Lagging.* At this power factor we find from Table II that there are 16 cases where the meter will run in the right direction. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c) 2 (b), 3 (d), 4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 11(a), 11 (b), 12 (c) and 12 (d).

The effect that is produced by an interchange of the voltage leads 1 and 2 is given in Table V. We find after interchanging the leads that for each of the four correct connections the meter will stop, and that for any one of the other 12 cases the meter disk will rotate either right or wrong.

Power Factor <0.5 *Lagging.* For a power factor of less than 0.5 we see from Table II that there are 20 cases where the meter disk will run in the correct direction, with all connections intact. These are as follows: 1 (a), 2 (d), 3 (b), 4 (c), 1 (c), 2 (b), 3 (d),

TABLE III—POWER FACTOR = 1.0

Case	Voltage leads 1 and 2 interchanged gives case	Directon of Rotation of meter then becomes
1 (a)	5 (a)	Stop
2 (d)	6 (d)	"
3 (b)	7 (b)	"
4 (c)	8 (c)	"
9 (a)	10 (a)	Wrong
9 (c)	10 (c)	"
10 (b)	9 (b)	"
10 (d)	9 (d)	"
11 (a)	12 (a)	"
11 (b)	12 (b)	"
12 (c)	11 (c)	"
12 (d)	11 (d)	"

TABLE IV—POWER FACTOR < 1 AND > 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (d)	3 (d)	Right
2 (d)	6 (d)	"	8 (a)	4 (a)	"
3 (b)	7 (b)	"	9 (a)	10 (a)	Wrong
4 (c)	8 (c)	"	9 (c)	10 (c)	"
1 (c)	5 (c)	Right	10 (b)	9 (b)	"
2 (b)	6 (b)	"	10 (d)	9 (d)	"
3 (d)	7 (d)	"	11 (a)	12 (a)	"
4 (a)	8 (a)	"	11 (b)	12 (b)	"
5 (c)	1 (c)	"	12 (c)	11 (c)	"
6 (b)	2 (b)	"	12 (d)	11 (d)	"

TABLE V.
POWER FACTOR = 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop
2 (d)	6 (d)	"
3 (b)	7 (b)	"
4 (c)	8 (c)	"
1 (c)	5 (c)	Right
2 (b)	6 (b)	"
3 (d)	7 (d)	"
4 (a)	8 (a)	"
5 (c)	1 (c)	"
6 (b)	2 (b)	"
7 (d)	3 (d)	"
8 (a)	4 (a)	"
11 (a)	12 (a)	Wrong
11 (b)	12 (b)	"
12 (c)	11 (c)	"
12 (d)	11 (d)	"

4 (a), 5 (c), 6 (b), 7 (d), 8 (a), 9 (b), 9 (d), 10 (a), 10 (c), 11 (a), 11 (b), 12 (c) and 12 (d).

These cases are treated in Table VI, and it is evident that the rotation of the disk, as before, only ceases when the original connections were correct before the leads 1 and 2 were interchanged, and that for all other arrangements, rotation either forward or backward will take place.

Power Factor <1.0 *and* >0.5 *Leading.* We find from Table II

TABLE VI
POWER FACTOR < 0.5 LAGGING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (d)	3 (d)	Right
2 (d)	6 (d)	"	8 (a)	4 (a)	"
3 (b)	7 (b)	"	9 (b)	10 (b)	Wrong
4 (c)	8 (c)	"	9 (d)	10 (d)	"
1 (c)	5 (c)	Right	10 (a)	9 (a)	"
2 (b)	6 (b)	"	10 (c)	9 (c)	"
3 (d)	7 (d)	"	11 (a)	12 (a)	"
4 (a)	8 (a)	"	11 (b)	12 (b)	"
5 (c)	1 (c)	"	12 (c)	11 (c)	"
6 (b)	2 (b)	"	12 (d)	11 (d)	"

TABLE VII
POWER FACTOR < 1.0 AND > 0.5 LEADING.

Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes	Case	Voltage leads 1 and 2 interchanged gives case	Direction of rotation of meter then becomes
1 (a)	5 (a)	Stop	7 (a)	3 (a)	Right
2 (d)	6 (d)	"	8 (d)	4 (d)	"
3 (b)	7 (b)	"	9 (a)	10 (a)	Wrong
4 (c)	8 (c)	"	9 (c)	10 (c)	"
1 (b)	5 (b)	Right	10 (b)	9 (b)	"
2 (c)	6 (c)	"	10 (d)	9 (d)	"
3 (a)	7 (a)	"	11 (a)	12 (a)	"
4 (d)	8 (d)	"	11 (b)	12 (b)	"
5 (b)	1 (b)	"	12 (c)	11 (c)	"
6 (c)	2 (c)	"	12 (d)	11 (d)	"

that under these conditions there are 20 cases where the meter will run in the right direction, with all circuits intact. These are: 1 (a), 2 (d), 3 (b), 4 (c), 1 (b), 2 (c), 3 (a), 4 (d), 5 (b), 6 (c), 7 (a), 8 (d), 9 (a), 9 (c), 10 (b), 10 (d), 11 (a), 11 (b), 12 (c), and 12 (d).

The effect of interchanging leads 1 and 2 on these cases is treated in Table VII. It is clear from Table VII that the rota-

tion of the disk, as for lagging values of the power factor, only ceases for the four correct connections when the interchange is made, and that for all other arrangements rotation either forward or backward will take place.

It may further be proved from Table II that for other values of leading power factor, an interchange of the voltage connections 1 and 2 will cause the rotation of the disk to cease for the four correct connections only.

It is evident from the above proof, that with a balanced load (motor load), the correctness of the connections of a polyphase watt-hour meter, provided with four voltage terminals, can be accurately checked at any power factor by the simple interchange of the voltage connections to the phases 1 and 2, when the meter is used without voltage transformers, and if the meter stops the original connections were correct.

The interchange may be easily and simply made at the meter terminals. The following set of rules for the identification of connections may be deduced from Tables II, III, IV, V, VI and VII.

1. If, after the interchange of voltage connections 1 and 2, the meter stops, then the original connections were correct.

2. If, after the interchange of voltage connections 1 and 2, the meter continues to run in the right direction at increased speed, then the original connection was either 1 (c) or 2 (b) or 3 (d) or 4 (a), for leading currents 1 (b), 2 (c), 3 (a) or 4 (d), and the reversal of the connections of one of the current coils is all that is needed to rectify the mistake.

3. If, after the interchange the meter continues to run "right" but at greatly reduced speed (one-half its former speed) then the original was one of the arrangements of 5, 6, 7 or 8 and the voltage connections are now correct. The reversal of the proper current coil is all that is needed to make the connections correct.

4. If, after the interchange the meter runs in the wrong direction, then the original connection belonged to arrangements 9, 10, 11 or 12 and the entire system of connections must be carefully gone over and corrected.

The theoretical expressions for P for each of the 24 additional arrangements, mentioned above, are given in Tables VIII and IX. As stated, twelve of these arrangements are formed by connecting two meter terminals to phase 1, one to phase 2, and one to phase 3; and twelve by connecting two terminals to phase 2. one to phase 1, and one to phase 3. In Tables VIII and IX the

unimportant arrangements similar to arrangements 9, 10, 11 and 12 of Fig. 2 have been omitted. The expressions for these unimportant arrangements may be found elsewhere if needed. For example, consider arrangement 9 of Table VIII. Arrangement 9, Table VIII, is made by connecting the voltage terminals of meter element I to phases 2 and 3, and by connecting both voltage terminals of meter element II to phase 1. The theoretical expressions for the resulting cases are to be found in Table II, arrangement 5, cases (e), (h), (k) and (n).

Checking the Connections

The elimination of the incorrect connections treated in Tables VIII and IX is accomplished by the interchange of voltage leads 1 and 2. If the wiring is open the interchange is made at the meter terminals, and in places where the wires to the meter run in conduit the interchange is made at the line. In either case the inspection of the connections incidental to making the interchange indicates at once the mistake, as it is apparent that two of the voltage terminals are connected to one of the phases that supply the current coils of the meter with current. The correction of the mistake is simple.

Class A Meters with Voltage Transformers

The addition of voltage transformers complicates the connections, and makes possible a large number of additional connections. That this is a fact is clearly seen when one considers that the twelve arrangements of connections shown in Fig. 2 may be applied to the primary side of the transformers, and that for each one of these there are 24 different possible arrangements of the connections between the four secondary terminals of the transformers and the four voltage terminals of the polyphase meter.

Four of these arrangements are shown in Fig. 5. However, it is evident that the four arrangements shown in Fig. 5 are electrically the same. A careful study of the conditions shows that no new electrical arrangements of the circuits are introduced by a combination of any one of the first eight cases applied to the primary side of the transformers with any one of the first eight arrangements between the secondaries of the transformers and the meter. The same is also true when any one of the last four cases on the primary side is combined with any one of the same cases on the secondary side. However, any combination

made with any one of the first eight arrangements on the primary side, with any one of the last four on the secondary side of the transformers, introduces new cases. In all of these new cases which are brought about by the addition of the voltage transformers, the two secondary windings of the transformers and the two voltage coils of the polyphase meters are in series. Two of these cases are illustrated in Fig. 6.

For any one of these added cases formulas for the rate and direction of rotation can be derived if necessary. These cases are not only very improbable, but a reversal of the voltage leads 1 and 2 on the primary sides of the transformers will in no case cause the meter to stop. Therefore, the use of voltage transformers does not introduce any new cases of importance, and the expressions given in Tables II, VIII and IX apply to this type of meter when used with transformers.

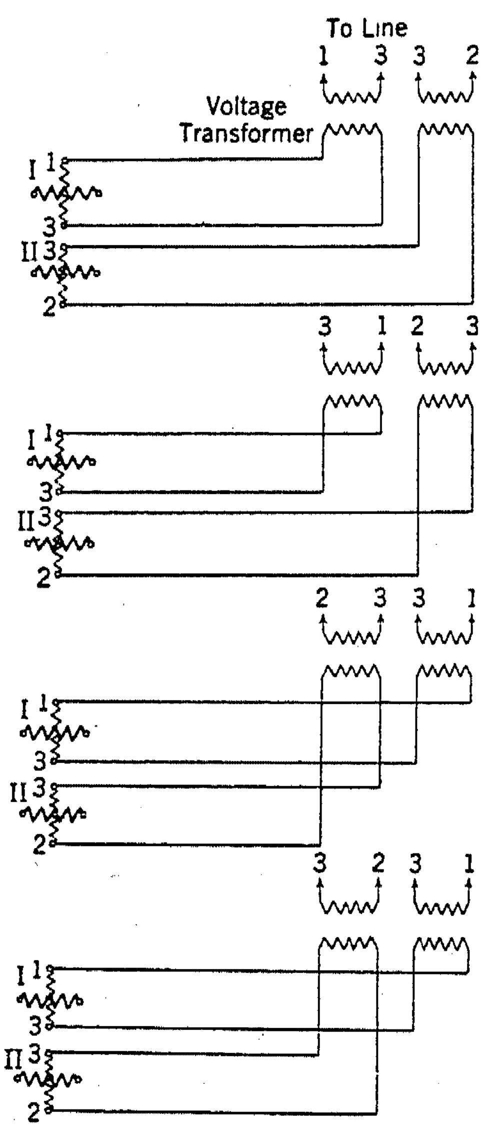


FIG. 5

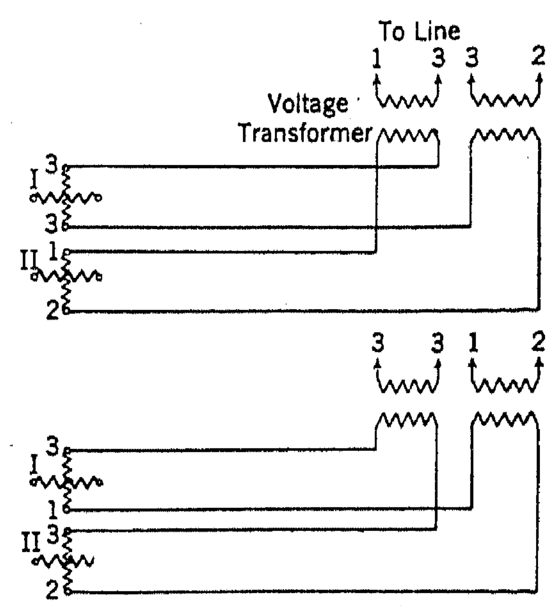


FIG. 6

Since the same expressions for P hold good, irrespective of the presence or absence of voltage transformers, the same mode of checking the connections is applicable in both cases. Therefore, the correct connections of a polyphase watt-hour meter, provided with four separate voltage terminals, when used with voltage transformers, may be checked by the interchange of voltage connections 1 and 2 on the primary side of the voltage transformers. And if the connections were originally correct, and the load is balanced, the meter will stop at any power factor. Further, if we assume that all of the improbable connections of cases 9, 10, 11 and 12 of Table II are absent, and that all incor-

rect connections illustrated in Tables VIII and IX will be eliminated by the inspection of the connections incidental to making the interchange, then we may apply rules 1, 2 and 3 for the correction of mistakes in the connections.

CLASS B METERS

The correct connections of Class B type of polyphase meter are shown in Fig. 7. With this class of meter the presence of voltage transformers does not introduce any new cases, and therefore the following discussion applies equally well to meters of this type when used either with or without voltage transformers.

The number of possible arrangements of the voltage connections to the three meter terminals is found to be six. These are

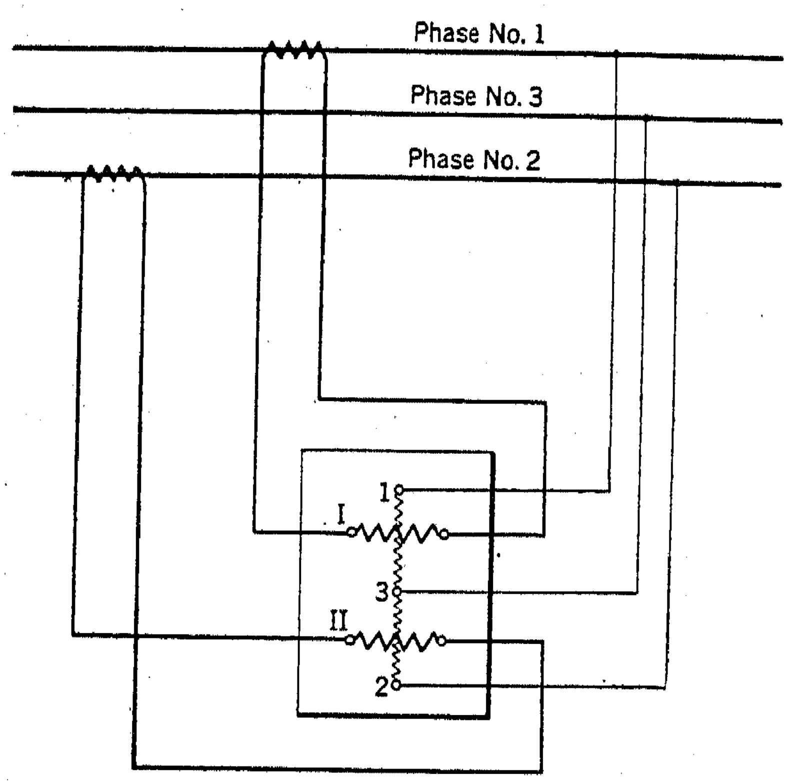


FIG. 7

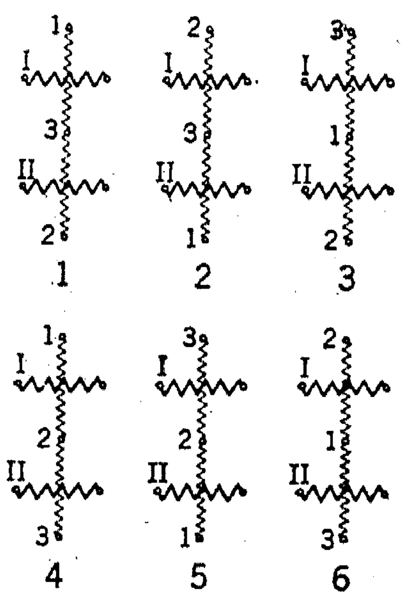


FIG. 8

shown in Fig. 8. As in the case of Class A meters, each arrangement of the voltage connections has four different arrangements of the current coils, and each arrangement of the connections of the current coils has four conditions of operation, depending upon whether all the voltage connections are intact or if one of them is open. Therefore, we find a total of 96 different connections or cases.

The theoretical expressions for P were derived for each one of the cases, and these are to be found in Table X. With this type of meter, the opening of the voltage connection 3 does not give a case analogous to those due to the opening of either leads 1 or 2, but a separate and distinct case. The following example will serve to illustrate the derivation of the value of P for these cases:

Case 1 (g) *Phase I and Phase II Correct, Voltage Lead 3 Open.*

The vector diagram is given in Fig. 9. The voltage is divided between the two potential coils of the meter, and therefore, half of the voltage is across each coil and we find that

$$P = \frac{1}{2} I_1 E_{1,2} \cos (30 + \Phi) + \frac{1}{2} I_2 E_{2,1} \cos (30 - \Phi)$$

$$P = \left(+ \frac{\sqrt{3}}{2} \cos \Phi \right) I E$$

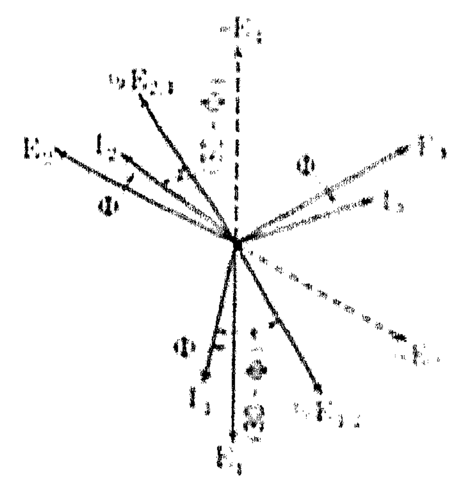


FIG. 9

The correctness of each of the 96 expressions was checked experimentally as in the case of the Class A type of meter. Table X not only gives the expressions but also the directions of rotation of the meter disk at several different values of lagging power factor.

CHECKING OF CONNECTIONS

From Table X we find that there are 60 cases where the meter will run in the correct direction at some power factor between unity and zero lagging, however, only 12 of these are for cases where all the circuits are intact. These 12 are as follows: 1 (a), 1 (c), 2 (c), 3 (b), 4 (b), 4 (c), 5 (b), 5 (c), 5 (d), 6 (a), 6 (b) and 6 (d).

Of these 12 cases there is only one case where the meter registers correctly under all conditions the amount of power consumed, and that is case 1 (a). A careful study of the table does not reveal any simple method of checking the correctness of the connections 1 (a) that does not apply equally well to some of the incorrect cases. The arrangements of connections that do not offer any simple means of elimination are cases 5 (d), 6 (a) and 6 (d). However, mistakes that are illustrated by cases coming under 3, 4, 5 and 6 are not often made, especially if the common voltage terminal of the meter to which phase 3 is connected is plainly marked. If this terminal is marked, it is practically impossible to make any mistake in its connection to the proper phase, and therefore, we need only consider cases coming under arrangements 1 and 2.

Under arrangements 1 and 2 of the voltage connections we find only three cases where the meter will run in the right direction. These are: 1 (a), 1 (c) and 2 (c). In addition to the check of the

correctness of the connections produced by the opening of the voltage supply to each element of the meter in turn, there is also a check that is sometimes employed with this class of meter which consists in opening lead 3.

The same criticism, namely, that it cannot be relied upon, that applied to the check obtained by opening the voltage supply of each element in turn, as applied to the Class A type of meter, applies equally well when used with this class of meters. When we study the effect of opening lead 3, we see from Table VIII that when we open lead 3 for case 1 (a) we get case 1 (g), and the meter continues to run in the right direction at exactly one-half speed. For case 1 (c) we get 1 (m) and the meter now runs in the wrong direction, and for case 2 (c) we get 2 (m), and the meter continues to run in the right direction at exactly one-fourth its former speed. Therefore, this check may be relied upon provided the load remains constant.

Check Produced by the Interchange of the Voltage Connections to Phases 1 and 2

At unity power factor we have only case 1 (a) possible and an interchanging of the voltage leads 1 and 2 will give case 2 (a) and the rotation of the disk will cease. This is also true of case 1 (a) for any value of the power factor either leading or lagging.

At all values of lagging power factor below unity, we may have in addition to case 1 (a) either 1 (c) or 2 (c). The interchange for voltage leads for the case 1 (c) gives case 2 (c) and the meter continues to run in the right direction at double its original speed. The interchange for case 2 (c) gives 1 (c) and the meter continues to run in the right direction at one-half its original speed.

For leading values of the power factor we find three cases where the meter disk will rotate in the right direction. These are: 1 (a), 1 (b) and 2 (b). In cases 1 (b) and 2 (b) the disk will continue to rotate in the right direction after the interchange is made.

It is evident from the above, that the interchange of the voltage leads 1 and 2 will serve to eliminate all incorrect connections and check the proper connections for Class B meters, if we allow the assumption that the common voltage terminal is connected to its proper phase, *i. e.*, to the phase that does not supply current to the current coils of the meter. This connection is very simple if the terminal is clearly marked. Rules 1 and 2 also

apply to this meter, and aid in the correction of mistakes. The interchange of leads 1 and 2 may always be made at the terminals of the instrument.

Class C Meters

The correct connections of the Class C type of meter are shown in Fig. 10. Instrument transformers are seldom used with this type of meter, which is essentially a house meter. The three possible arrangements of the voltage connections are illustrated in Fig. 11.

The expressions for P and the direction of rotation at different power factors are given in Table XI.

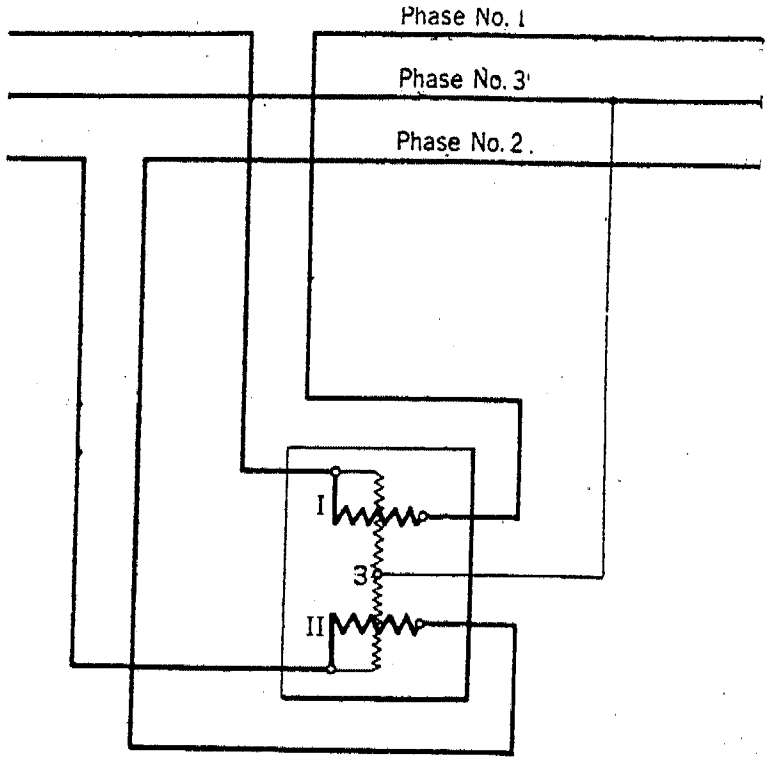


Fig. 10

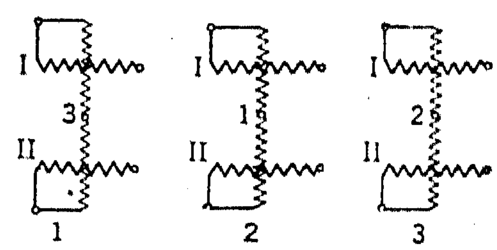


Fig. 11

Checking the Connections

Table XI shows that there are 8 cases where the meter will run in the right direction at some value of the power factor, when all its circuits are intact. Of these 8 cases, case 1 (a) is the only case or arrangement of connections where the meter will operate correctly under all conditions. The 8 cases are: 1 (a), 1 (c), 2 (a), 2 (b), 3 (a), 3 (b), 3 (c) and 3 (d).

The check for this class of meters consists in opening the single voltage connections to the meter*; for case 1 (a) this gives 1 (g) and the meter continues to run in the right direction at one-half its former speed.

The opening of the voltage connection for case 1 (c) gives case 1 (m) and the meter stops or runs in the wrong direction, depending on the power factor. The opening of the voltage connections for any one of the remaining cases causes the meter to stop under all conditions. It may be stated that a balanced load is not essential for making the test.

* *Electrical World*, Vol. 63, p. 144, 1914.

Opening the Supply as a Method of Checking the Connections

In addition to the above-mentioned checks there is a test of the correctness of the connections that may be applied where it is permissible to open one phase at a time of the supply without interrupting the load. A phase must be opened in two places at the same time, namely, between the meter and the supply line and between the meter and the load.

This test is as follows: Assume that the meter is connected in a three-phase circuit, where one of the phases may be opened without interrupting the load. Now, with the meter running in the right direction, open one of the phases that supplies current to one of the current coils of the meter as directed above. The meter should continue to rotate in the right direction if the connections are correct; because it is now operating as a single-phase meter, registering the power supplied to a single-phase load. Replace the fuses and open the phase that supplies current to the other current coil of the meter. The meter should continue to rotate in the right direction for the same reason as before. If the meter stops or if its direction of rotation changes when either line is open, then the connections are incorrect and must be carefully traced out and the mistake rectified. In making this test it is not necessary to know the power factor of the load nor is a balanced load necessary.

Each phase that supplies current to the meter must be opened in two places during this test. If only a single opening is made between the meter and the load, both voltage coils of the meter will still be excited, and we may have such incorrect connections as cases 5 (c) 5 (b), 7(d), 8 (a) of Table II or 2 (c) of Table X which also give rotation in the right direction with either line open. If a single opening is made between the meter and the supply line and if the load consists of an induction motor or other similar apparatus, both voltage coils will still be excited due to the voltages induced in the motor windings, and we may have incorrect connections as above. Therefore, it is necessary to open the same phase of the circuit in two places simultaneously.

Example of the Application of the New Method

The following is an example of the application of the method of checking the correctness of a polyphase watt-hour meter on a three-phase circuit by means of the interchange of voltage connections to phases 1 and 2. For this example the writer has

assumed that we have to install a polyphase watt-hour meter with four voltage and four current terminals on a circuit requiring the use of voltage and current transformers. While making the test, the load on the circuit must be balanced and may consist of a three-phase induction motor, a three-phase bank of transformers or other similar apparatus. As it is difficult to obtain a balanced load with lamps, the lighting circuits should be open.

Connect the meter according to the diagram of connections (see Fig. 12) so that it rotates in the right direction.

Having obtained rotation in the right direction, interchange the connections on the primary side of the potential transformers to phases 1 and 2, and if rotation ceases the original connections were correct, and should be restored.

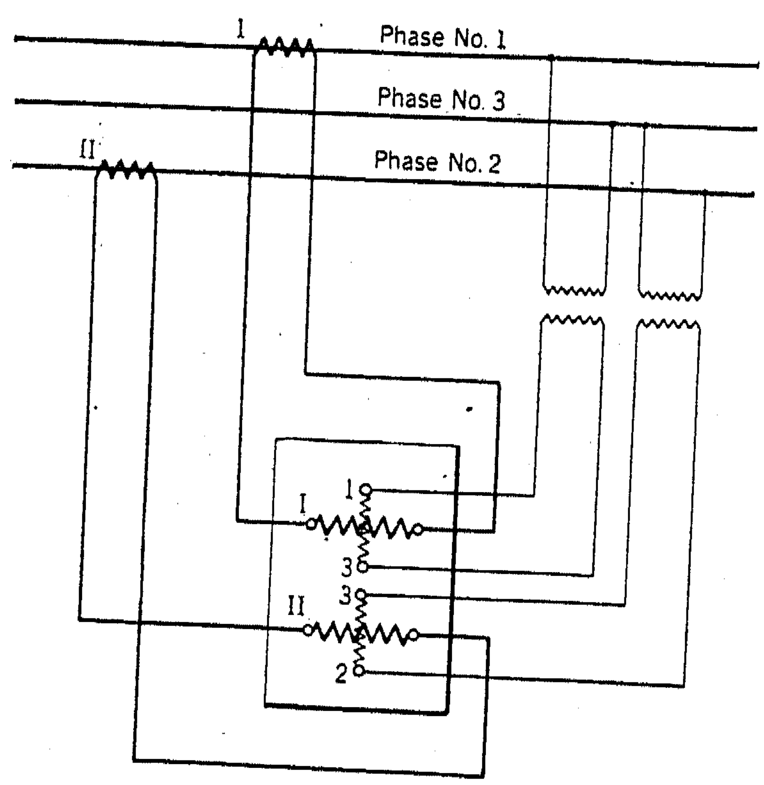


FIG. 12

If after making the interchange, the meter continues to run in the right direction but at increased speed, the original connections were correct, but the connections of one of the current coils were reversed. Restore the voltage connections to their original condition and reverse the connections of the current coil that will give rotation in the right direction after reversal.

If, after making the interchange, the meter continues to run in the right direction, but at reduced speed, the voltage connections are now correct, and one current coil is reversed. Reverse the connections of the current coil that will give rotation in the right direction after reversal.

Having satisfied the conditions of the test, the voltage terminals of the meter that are at the same potential may be connected together and grounded if desired.

Summary and Conclusions

The results of the investigation show clearly, first: That the check upon the correctness of the connections made by opening the current or voltage supply to each element in turn, is unreliable and may lead to erroneous results. Furthermore, a knowledge of the power factor is essential to its use.

Second: That the check upon the correctness of the connections made by opening the voltage connections to the phase that does not supply current to the two single-phase elements of the meter is only accurate in case of meters of Class C or to meters similarly connected.

Third: That the check upon the correctness of the connections made by opening in turn each of the three-phase lines that supply current to the current coils of the meter, is accurate at any power factor and on balanced or unbalanced load; provided the opening is made between the meter and the supply line.

Fourth: That the check upon the correctness of the connections made by the interchange of voltage connections to phases 1 and 2 is accurate at any power factor on a balanced load for Class B meters, if we make the assumption that phase 3 is connected to the proper terminal and that if the original connections were correct the meter stops. This also applies to meters having four voltage terminals when two of these are connected together, and from a common terminal.

Fifth: That the check upon the correctness of the connections made by the interchange of voltage leads 1 and 2 is accurate at any power factor on a balanced circuit for Class A meters, and that if the original connections were correct the meter stops.

Sixth: That in case the connections are incorrect for Class A and B meters, the interchange of leads 1 and 2 gives the necessary information for correcting the mistake (see Rules 2 and 3, page 172).

The investigation also shows that there is a simple means of ascertaining the power factor on a three-phase circuit where a polyphase watt-hour meter is installed. This method may be used with any type of meter. It is as follows: Note the time of one revolution of the disk when the meter is connected correctly and registering the given load. Then reverse the connections of either current coil, and note the time of one revolution, with the given load. Then

$$\tan \Phi = \frac{\sqrt{3}\,(\text{Time of one revolution, meter connected correctly})}{\text{Time of one revolution with one current coil reversed}}$$

The experimental work connected with this investigation was carried on in the new electrical laboratories of the Johns Hopkins University. The writer wishes to thank Mr. J. R. Cruikshank, Dr. J. B. Whitehead, Mr. F. V. Magalhaes and Mr. W. S. Brown for their kindness and assistance.

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DISCUSSION ON "A METHOD OF DETERMINING THE CORRECTNESS OF POLYPHASE WATTMETER CONNECTIONS" (KOUWENHOVEN), NEW YORK, FEB. 9, 1916.

W. H. Pratt: The author has made a very large amount of painstaking effort in collecting and analyzing the behavior of the meters with these miscellaneous connections. There is one point that is emphasized throughout the paper, that this checking must be made under balanced load conditions except in one particular case. There should be a great deal of care exercised in deciding whether you have a balanced condition in applying the check. The fact that you use a motor which tends to take a balanced load does not necessarily mean that the load will be balanced unless the voltages are strictly balanced. A very small unbalancing of voltage may mean a very large amount of unbalancing in the power station. This point emphasizes the fact that you should always be very particular in following the diagrams of connections. It is a very easy matter to systematically arrange most work so that you can follow the diagrams just as if you had a column of figures to add, and then very carefully do the work. There is a temptation, however, to rely on the check, but a check should be made bearing in mind that you have limitations which might seriously affect the conclusions.

Again, if you find that you have trouble it may be a very difficult matter to locate the cause of it. I have in mind a case which was called to my attention not many months ago in which all ordinary checks applied indicated that the connections were correctly made, even to tracing out the wiring, but there was evidence of something seriously wrong. When we came to trace it down, it appeared that there were two sets of instruments on the switchboard, the switchboard being in two parts, and the connection that was supposed to be a ground connection, simply served as a common zero potential connection. The two parts of the board were each individually connected up all right, but it so happened that the instruments on one portion required to have a common connection with the instruments on another portion, and this common connection was omitted, and there was a most mystifying behavior of the apparatus.

The author says that meters which he designates as class C meters cannot be used with either voltage or current transformers. Of course, it is quite possible to use such meters by making interconnections of the circuit, and making a simple interconnected secondary network.

Again, the remark is made: "By the use of the table it is also possible in cases where incorrect or open connections are found, to determine from the meter readings, when the conditions of the circuit are known, the actual kw-hr. that have been used." I think the expression of the author "when the conditions of the circuit are known" should be very much emphasized, because ordinarily the conditions of the circuit are such that the loads

are not of definite power factor, and unless that is true throughout the whole period of operations, no conclusions could be drawn.

G. A. Sawin: The author's methods of making his calculations are the same that I have followed for some years, but I have laid out my diagram a little differently. For example suppose we find a meter connected in a certain manner Fig. 1 and desire to know its accuracy; we make a diagram, Fig. 2. We find the current coil of element A is in line 1, and the current coil of element B is in line 3. The potential of element A is connected from 1-2 and of element B from 3-1 as shown. I have shown an incorrect connection for the purpose of illustration. Now we must always remember that the meter records exactly what it received, no matter whether it is the true power or not. In other words, if we treat each element in this case as a single-phase meter, and remember the measured power equals the voltage received times the current received, times the cosine of the angle of lag between this particular current and potential, we will immediately see what each element is measuring. Add the results of the two elements together, and we will have the total

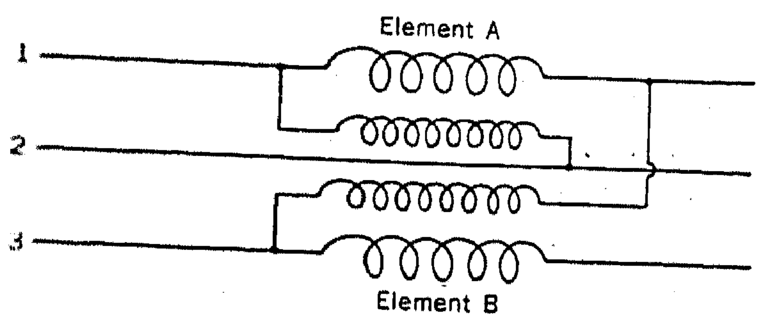


FIG. 1

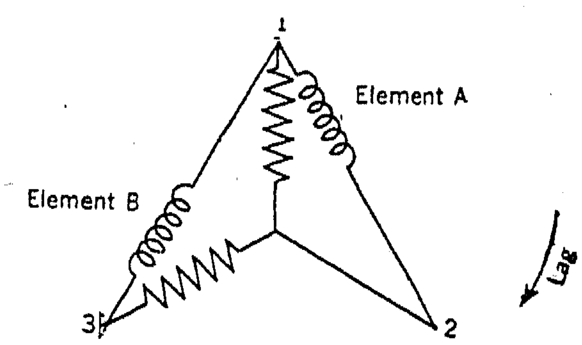


FIG. 2

measured power. Compare this result to the true power, and the correct answer is obtained. In this case the measured power is $E\,I \cos(30° + a) + E\,I \cos(30° + a) = 2\,E\,I \cos(30° + a)$.

The diagram to me personally is clearer, and shows exactly how to arrive at correct results in any case.

Mr. Pratt has called attention to the fact that in applying the author's method, we must have a balanced load. If we have an unbalanced load the results will not always come out, as expected. We often find cases where we have single-phase motors connected across two of the wires of the three-phase circuit, and sometimes we have lights connected so that in practise we should apply this method with caution.

Another point which the author does not bring out, but which is important, is that, after a meter has been in service for some time, we do not know whether it is in correct calibration or not. The author assumes all through his paper that the meter he is dealing with is correct. We can very readily imagine the case of an incorrect meter, for example, one which is badly out on lag, which would not answer correctly the test given here by the author. Therefore, in practise we must bear in mind, the

balanced condition of the load and whether the meter is correctly or incorrectly calibrated.

L. W. Chubb: We must remember that there are two classes of men that take care of meter connections—there is the engineer who knows the vector relation of the voltage and current, and if he gets irregular results in one way, he can usually ferret out what is the matter, either by symmetry of connections or by common horse sense. The station man who gets into trouble, must be provided with some rule of thumb method which will give him results and not require basic knowledge of the principles involved. For this reason I think Mr. Kouwenhoven's scheme of reversing the potential coils for two classes of meters, or else opening the current between the meter and power in the other class, is of great value.

The requirements for balanced load in the majority of the work is, as Mr. Pratt says, a handicap. A balanced load on such a thing as an induction motor, or light running synchronous machine, is rare. If the field distribution in the motor does not agree with the line wave, there will be quite a big distortion and an unbalancing of currents with a very small change in phase and voltage. I do not believe this is a serious handicap, however, as you can estimate about what load you have, and if the meter comes nearly to a standstill, you know that the connection is probably right. The same is true for a meter a little bit out of calibration in the two parts, as the last speaker has mentioned.

I think, that for the engineer who goes out on a meter job and wants to find out what is wrong, the old method of opening one element of the polyphase meter and then the other is pretty good. You can usually get a load, balanced or unbalanced, which will have a power factor both above and below 0.5. For instance, the usual transformer of today on open circuit is run at such an induction that the exciting current is below 0.5 power factor. It is easy enough to put additional load on the transformer, and take another reading at a power factor above 0.5 so that opening one element at a time, with the two tests, will give quite a reliable result.

Comfort A. Adams: The subject of polyphase meter connection is so often made unnecessarily complicated that I am going to take enough time to explain what seems to be the natural and simple point of view, which I have employed for more than twenty years.

Label the mains of a three-phase system, a, b and c. Count the currents in a and b as positive when flowing outwards from the source and the current in c positive backwards. Then will $i_a + i_b = i_c$ at every instant, and c may be looked upon as the common return for a and b. The total power flowing outwards from the source will then be that of two circuits ac and bc, or stated in symbols, $e_{ac}\, i_a + e_{bc}\, i_b$, which holds for every instant of time irrespective of whether the system carries direct, alternating or pulsating current.

The two single-phase wattmeters or the two parts of a three-phase wattmeter connected with their currents coils in a and b and their pressure coils across ac and bc respectively in the direction indicated by the symbols, will measure the average values of $e_{ac}\, i_a$ and $e_{bc}\, ib$ respectively, or a three-phase wattmeter will indicate the sum of these, *i. e.*, the total power flow of the system in the direction indicated. If the corresponding terminals $\pm$ of the current and pressure coils of each meter are so indicated or implied by their location, it is only necessary to connect the two current coils in the lines a and b in the direction of power flow and the corresponding pressure coils in the directions ac and bc. If the direction of power flow is not known, it may be assumed and connections made accordingly. If the assumption is correct, the meter will read or run positively, otherwise either both current coil connections or both pressure coil connections should be reversed.

The above proof of the two wattmeter method of three-phase power measurement as well as the resulting conclusions as to the method of connection, is absolutely rigid and general for any wave shape or no wave shape. Moreover, it is directly applicable to a system of n wires in which one is looked upon as the common return for $n - 1$ phases, and the power can be measured by $n - 1$ wattmeters (or wattmeter elements of a polyphase wattmeter) connected as above indicated for the three-phase case.

I realize that the problem faced by the meter man is not the same as that faced by the laboratory man; but I feel quite sure that even the practical meter man would find his problem vastly simplified if he could acquire the above described natural point of view.

The idea is not at all a new one, but so few engineers seem to make use of it, that I am impelled by my teacher's instinct to set it forth again.

W. B. Kouwenhoven: As stated in the paper, the term correct, refers only to the direction of rotation of the disc of the watt-hour meter used in this investigation, and has nothing whatever to do with the accuracy of the meter. The meter used was not calibrated before making the investigation and it had seen a number of years of service. I do not know whether the two single-phase elements had exactly the same characteristics or not. However, their characteristics were sufficiently alike to cause the meter to stop when the voltage connections to phases 1 and 2 were interchanged. If a polyphase watt-hour meter is so badly out of adjustment that it will not answer correctly to the test although connected properly: then its failure to meet the test will immediately indicate that there is something wrong with the meter itself.

As Mr. Chubb pointed out, a slight unbalancing of a three-phase load such as is often found in induction motors, especially when operating on light loads, is not serious, and the check produced by the interchange of the voltage leads will identify the

correct connections. Part of the investigation was carried on with induction motors as load, and part with synchronous motors, and in neither case was there the slightest difficulty in recognizing the correct connections when the check was applied. I do not know the amount of unbalancing that would prove serious. The correctness of the connections on balanced or unbalanced three-phase circuits for any class of meter may be checked by removing the fuses from the line as described in the paper.

If a polyphase watt-hour meter is placed in a circuit where no instrument transformers are required, then its proper connection, as Professor Adams points out, is comparatively simple. If two voltage and two current transformers are added to the circuit then the connections become difficult and a check is necessary.

Presented at the fourth Midwinter Convention of the American Institute of Electrical Engineers, New York, February 9, 1916.

THE TRUE NATURE OF SPEECH

With Application to a Voice-Operated Phonographic Alphabet Writing Machine

BY JOHN B. FLOWERS

Abstract of Paper

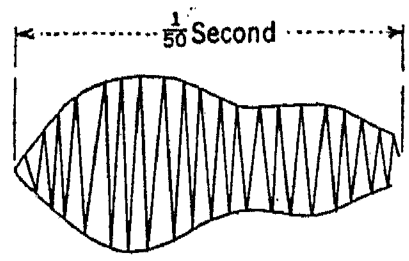
That speech is a rapid variation in intensity of the voice and mouth-tones according to definite sound patterns called letters of the alphabet, is proved, by showing that speech is the result of action of the mouth-parts in varying the intensity of the voice and mouth-tones, and through photographs taken with the string-galvanometer of each letter sound of the alphabet, showing definitely the characteristic variation in intensity of tone for each letter of the alphabet. From the curves, the phonographic alphabet is obtained by measuring the variations in intensity of the main tone of the record.

A design for a voice-operated phonographic alphabet writing machine is described. The object of this device is to record speech automatically in ink on paper in the form of an easily read compact system of natural characters called the phonographic alphabet. Its design comprises a high-power telephone transmitter controlling electric resonator circuits, the intensity of currents in which is measured by the vibration of mirrors reflecting light upon a selenium cell connected to a special recording pen.

Definition of Speech

SPEECH is a rapid variation in amplitude of one or more tones, there being a definite form of variation making a pattern for each letter sound of the alphabet. These patterns are not formed by the superposing of tones of different pitch to give a certain quality to the tone but by a definite form of variation in the amplitude of a single tone or tones. This previously unknown form of variation of amplitude, quite different from the ordinary change from soft to loud, should be called the speech-variation. What is meant is that if a tone of a pitch of say 1000 cycles per second commences in such a manner that the first 10 to 20 cycles vary in intensity after the definite pattern , the sound *b* will be produced and heard.

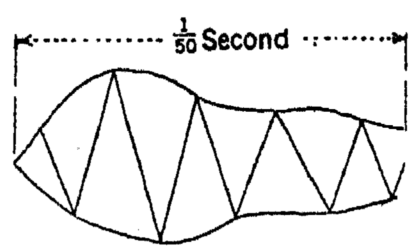
Thus:



20 Cycles of a 1000-Cycle Tone

But no matter what the pitch of the tone, if its intensity is made to vary according to this definite pattern in a *small fraction of a second*, the sound *b* will be produced.

Thus:



5 Cycles of a 250-Cycle Tone

When we speak the letter *b*, the fundamental tone and the overtones of the vocal chords together with the mouth-tones are all varied at the same instant of time according to the definite pattern. The same is true for each letter sound of the alphabet, as will appear in the table of patterns of the letters of the alphabet called the phonographic alphabet on another page:

In other words, if an open reed-organ pipe of, say, middle C pitch were blown and at its large open end were placed a mechanical device like the human mouth for opening, varying the opening, and closing the opening, and trilling and varying the air pressure, the organ pipe would speak like a human being, with wonderful power and majesty.

We quote Helmholtz: "Sensations of Tone," pages 66-67-68. "There has been a general inclination to credit quality with all possible peculiarities of musical tones that were not evidently due to force and pitch. But very slight consideration will suffice to show that many of these peculiarities of musical tones depend upon the way in which they begin and end. The methods of attacking and releasing tones are sometimes so characteristic, that for the human voice they have been noted by a series of different letters. To these belong the explosive consonants *B*, *D*, *G*, and *P*, *T*, *K*. The effects of these letters are produced by opening the closed, or closing the open passage through the mouth. For *B* and *P* the closure is made by the lips, for *D* and *T* by the tongue and upper teeth, and *G* and *K*

by the back of the tongue and soft palate. In wind instruments where the tones are maintained by a stream of air, we generally hear more or less whizzing and hissing of the air which breaks against the sharp edges of the mouthpiece. It is well known that most consonants in human speech are characterized by the maintenance of similar noises, as F, V; S, Z; Th in thin and in then; the Scotch and German guttural CH, and Dutch G. For some the tone is made still more irregular by trilling parts of the mouth, as for R and L. In the case of R the stream of air is periodically entirely interrupted by trilling the uvula, or the tip of the tongue; and we thus obtain an intermitting sound to which these interruptions give a peculiar jarring character. In the case of L the soft side edges of the tongue are moved by the stream of air, and, without completely interrupting the tone, produce inequalities in its strength. The formation of M and N in so far resembles that of vowels, that no noise of wind is generated in any part of the cavity of the mouth, which is perfectly closed, and the sound of the voice escapes through the nose."

Proof that a Definite Fixed Pitch is Not the Chief Characteristic of Individual Letter Sounds

Anyone may easily prove this for himself. Place upon the phonograph a talking record. Run the record, first at 60 revolutions per minute, which is below the normal speed, then at 160 revolutions per minute, which is $2\frac{2}{3}$ times the lower speed. The articulation remains intelligible even at the low and high speeds. The pitches of all speech sounds at the high speed of the record are nearly an octave and a half above the pitches at the low speed. Hence if but one fixed pitch was characteristic of each letter sound, the speech would have been absolutely unintelligible. But the speech was entirely intelligible and therefore pitch is not the distinguishing element between letter sounds.

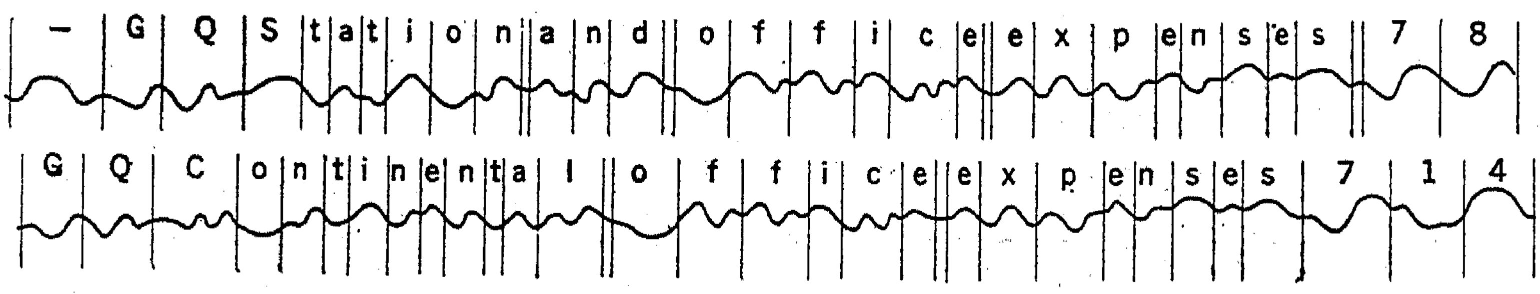
Definition of Vowels and Consonants

A vowel is a definite sound pattern which repeats itself at intervals, while a consonant is a definite sound pattern occuring but once. The consonant sound pattern must exist at least for 0.01 second, in order to be perceived by the brain, 0.01 second being the minimum perception time for speech sounds. The vowel sound patterns proper, are about 0.01 second in duration, but as they repeat themselves again and

again, may be of any duration the speaker desires. Under this definition, the consonants are b, c = k, d, g, j, k, p, t, and the vowels are, a, c = s, e, f, h, i, l, m, n, o, r, s, u, v, w = $\overline{\text{uo}}$, y, z.

Written language is made up of consecutive pattern pictures, one pattern or form standing for each letter of the alphabet, and the eye is able to distinguish between them if they approximate the standard form. Likewise, spoken language is made up of consecutive pattern pictures, one pattern or form standing for each letter of the alphabet, and I show in another paper not yet published, how the ear is able to distinguish between them when they approximate a standard form.

In reading a submarine cable message on the tape, the eye must pick out the pattern forms of each letter. That the eye can read these messages as fast as ordinary writing is known to all cable operators. Spoken language is similarly a succession of these different pattern forms, strung along one after the other, and the ear distinguishes each of these pattern forms as it arrives in the consecutive order of utterance, even as the eye distinguishes pattern forms of written or submarine cable language.



CABLE MESSAGE RECEIVED BY THE W. U. TELEGRAPH CO., FEBRUARY 11, 1915, OVER AN ATLANTIC CABLE

Speech may be whispered using no voice (without movement of the vocal chords). This fact was determined by actual observation of quiet vocal chords during a whispered word, "ah."

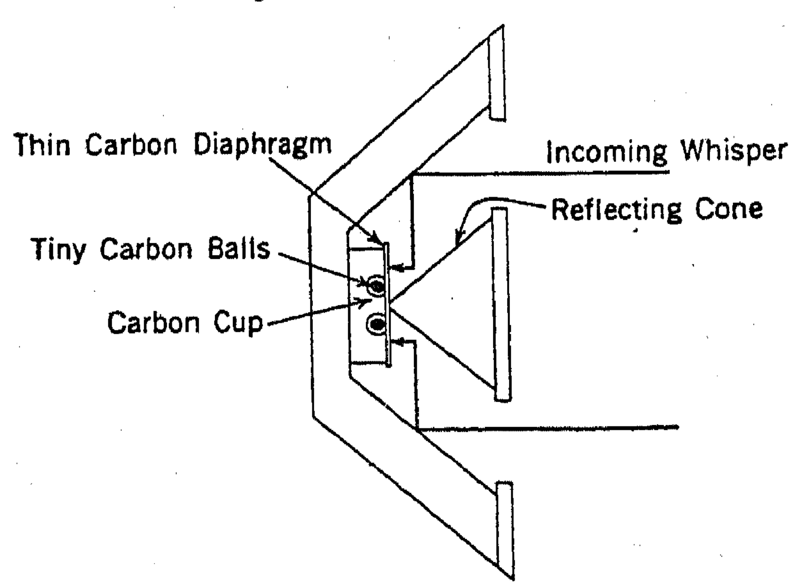
DISTINCTION BETWEEN SPEECH AND VOICE

Note the distinction between speech and voice and where each is produced, viz., voice by the vocal chords and speech through variation in the intensity of the compressed air forced through the throat, mouth, and nasal cavity. This variation in intensity is accomplished by the action of the muscles of the throat and mouth. Each person has a slightly different pitch of voice, men low and women high. An average man's voice has a pitch lying between 85 and 160 complete vibrations per

second, while the average woman's voice has a pitch lying between 150 and 320 complete vibrations per second. Thus, the pitch of one person's voice is different from another's.

But speech may be produced by whispering, that is, using no voice, and whispered speech always has the same sound, no matter who is the speaker, man or woman. Any person can determine this by his own observation, getting someone to whisper with him and comparing the sound of the whispers. No difference in the sound of the whispers can be heard. In other words, during a wh'sper, speech is independent of the vocal chord action.

All previous speech records have been taken of spoken or sung words and none of whispered words on account of the lack of instruments sufficiently sensitive to record whispered speech. The resulting spoken records contained the fundamental tones and overtones of the vocal chords as well as the mouth-tones and their variations combined in so complex a curve that no one has as yet succeeded in deciphering them.



SECTION OF ACOUSTICON TRANSMITTER FOR WHISPERED SPEECH

I found that the acousticon transmitter hooked up to the Einthoven string-galvanometer, as shown in the sketch herewith, were very satisfactory instruments for making records of whispered speech, as they are both marvelously sensitive instruments. On account of whispered speech being independent of vocal chord action, it was decided to make photographic records of it from which to determine by careful study the true nature of speech. It is evident that the whispered speech records will not show the voice-tones and overtones but will simply show the mouth-tones and their variations in intensity. It is easy to follow the variation in intensity of one or two tones on the whispered speech records and thus pick out the intensity pattern for each letter sound which I call the phonographic alphabet.

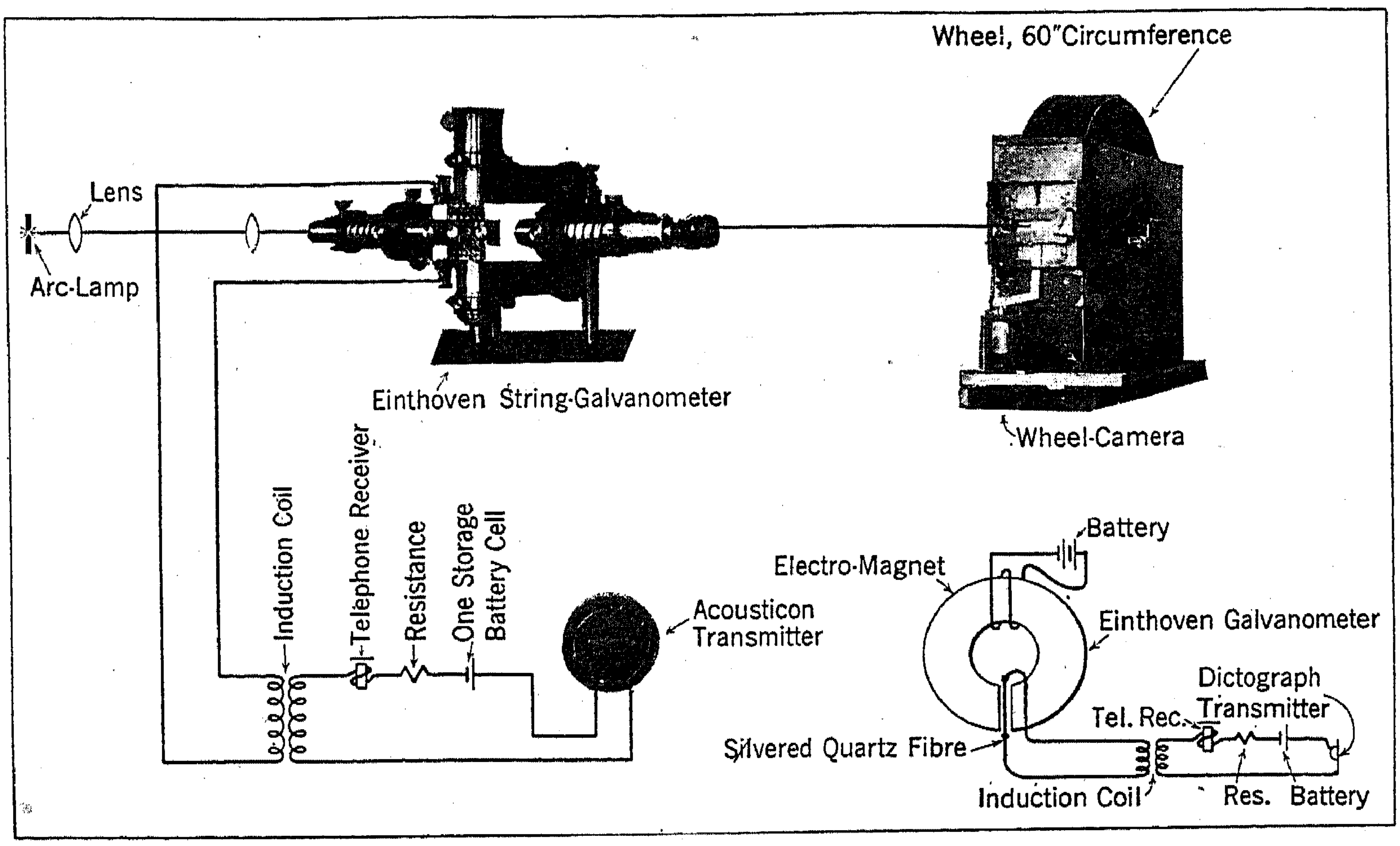
The diaphragm is made of very thin carbon and so covers the recesses in the carbon block, without touching it, as to prevent the tiny carbon balls from falling out. The sketch shows how the acousticon transmitter collects sound from a large area and by a reflecting system concentrates it on the middle of the carbon diaphragm. There is no spring pressing on the diaphragm and it is believed that the diaphragm moves like a piston with the rarefactions and compressions of the sound waves. It is a highly damped instrument due to the weight of the carbon balls pressing against the diaphragm resisting its motion.

Description of Method of Making Whispered Speech-Pattern Pictures

The acousticon transmitter was placed in a large sound-proof telephone booth and supported by suspension, free of all vibration. The diagram shows how the speech current flows from the acousticon through the storage battery cell, through the resistance, through the telephone receiver, through the primary side of the induction coil, and back to the acousticon; on the secondary side of the induction coil, the speech current flows through the string of the galvanometer. The string galvanometer is an electrical instrument having a fine silver-plated quartz fiber, 0.0001 in. thick, supported between two poles of a huge electromagnet. Through a hole in the magnet poles, a powerful ray from an arc lamp is focused upon this quartz fiber or string. By means of another system of lenses, the image of the string is focused upon a slot in the rotating drum-camera. When a speech-current flows through this galvanometer string, the string vibrates back and forth in a direction at right angles to the lines of force of the magnet, and its lightest motion is magnified 900 times by the lens system. The shadow of the string vibrates back and forth on the camera-shutter almost exactly in proportion to the speech sounds. The camera photographs the vibrating shadow of the galvanometer string. A word is whispered repeatedly, and the speech is listened to in the telephone receiver as a check on the articulation of the words. When the shadow of the galvanometer string moves back and forth about two inches, a lever is pressed, the electrically operated camera-shutter is held open for one revolution of the wheel and a photographic record, five feet long, of the word whispered is obtained. Extra-rapid film was exposed and good photo-

graphs obtained at rates varying from 1000 feet to one mile per minute. The rate of 1080 ft. was used mostly in this work as it gave a record with good intervals between crests of speech-waves, the best record to analyze. By interrupting the light from the arc lamp, 500 times per second, vertical lines were photographed upon the film at intervals of 0.002 second by a specially constructed time-wheel, for the necessary time record.

For a consideration of the theory of the string galvanometer, I refer to Dr. A. C. Crehore on the "Theory of the String Galvanometer," *Phil. Mag.*, vol. 28, August, 1914. The amount of air and electromagnetic damping of the movement of the galvanometer string was large enough, so that the motion of

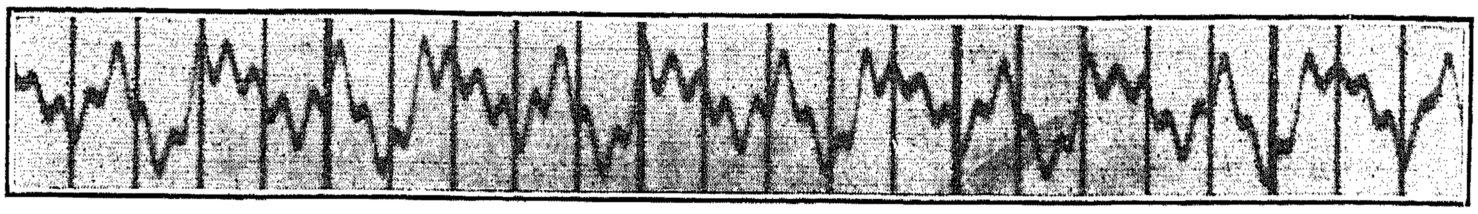


the string corresponded almost exactly to every component of the impressed speech currents, and the resulting speech records should be regarded as being as nearly correct records of speech as can be obtained by any recording instrument.

Speech patterns of the same letter sound are almost exactly identical for all persons and independent of age or sex of speaker. Five hundred records were obtained of three men's speech and one woman's speech which prove this.

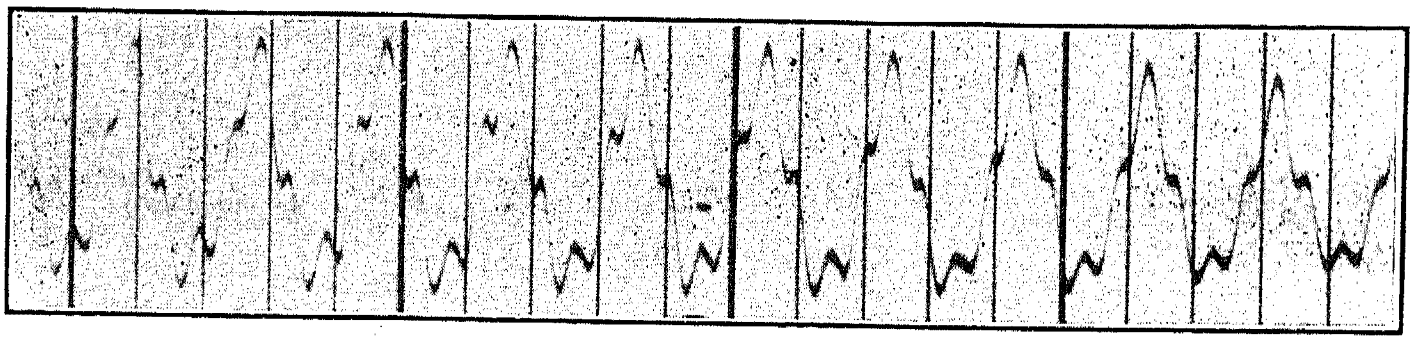
The Pattern Forms of the Natural Alphabet

Each of the letters has its own pattern form. All following records are of whispered speech, except Nos. 1 and 2.



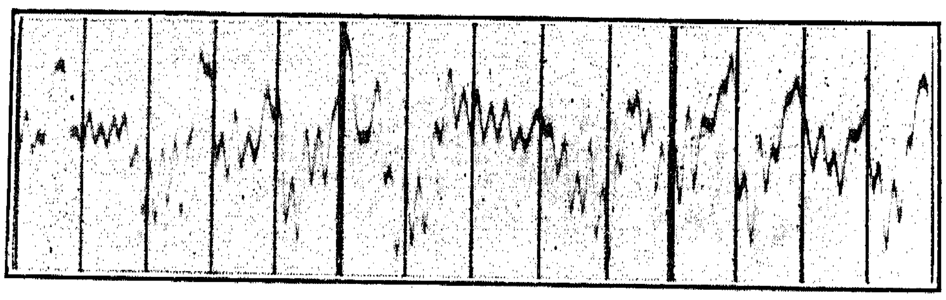
CURVE 1— ū in yū

Showing fundamental tone of voice to be 140 to 200 cycles per second. ū equals 1100 cycles per second superposed upon the lower note in definite pattern form. Male voice, spoken record.



CURVE 2—ū in yū

Fundamental tone of voice shows 250 cycles per second. ū shows 1050 cycles superposed upon 250 cycles per second in definite pattern form. Female voice, spoken record.

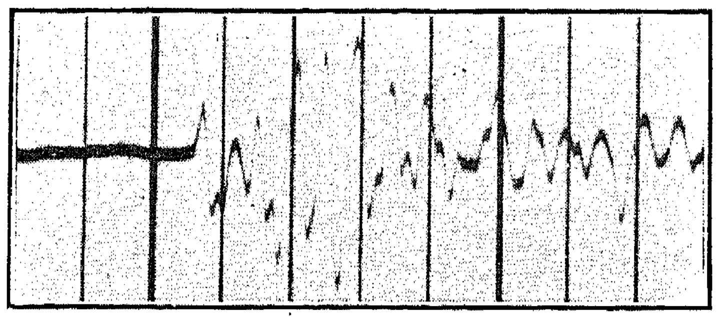


CURVE 3—ā in āō

ā shows 2500 cycles per second superposed upon 500 cycles per second in definite pattern form. (Repeating pattern picture.)

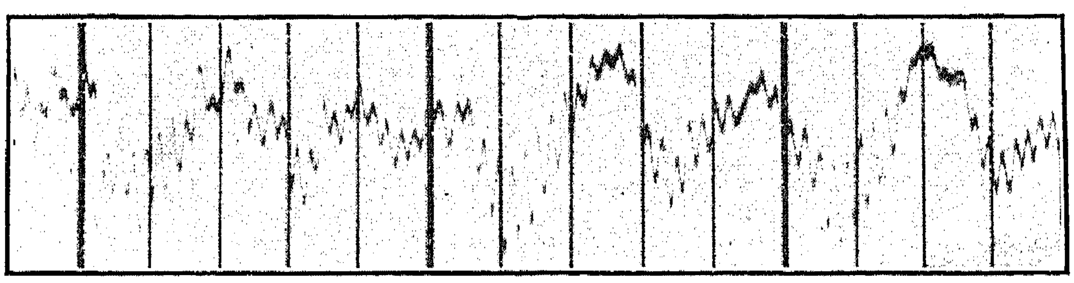
CURVE 4—b in bāy

b shows special pattern picture.
c equals s.



CURVE 5—d in dāy

d shows special pattern picture.

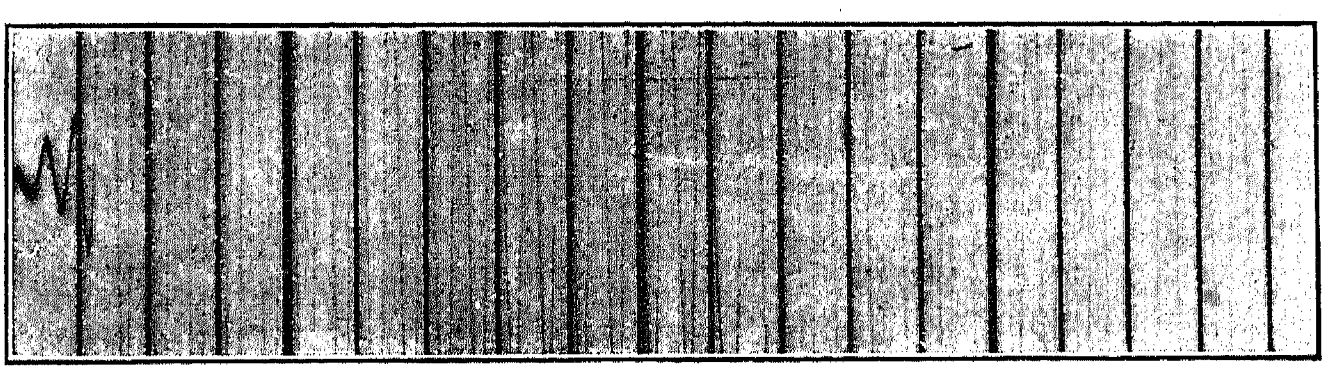


CURVE 6—ē in mē

e in me, shows 2500 cycles per second superposed on 200 cycles per second in special pattern picture. (Repeating pattern picture).

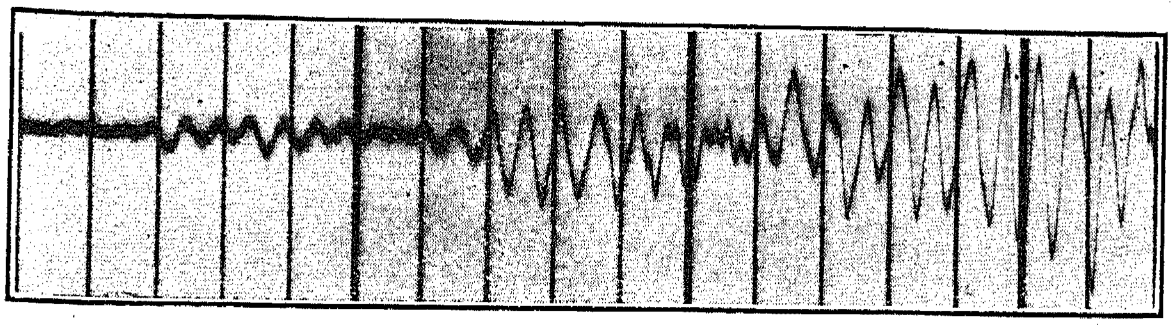
CURVE 7—f in fēē

f in fēē, shows alternation of 1000 and 2500 cycles, special pattern. (Repeating).



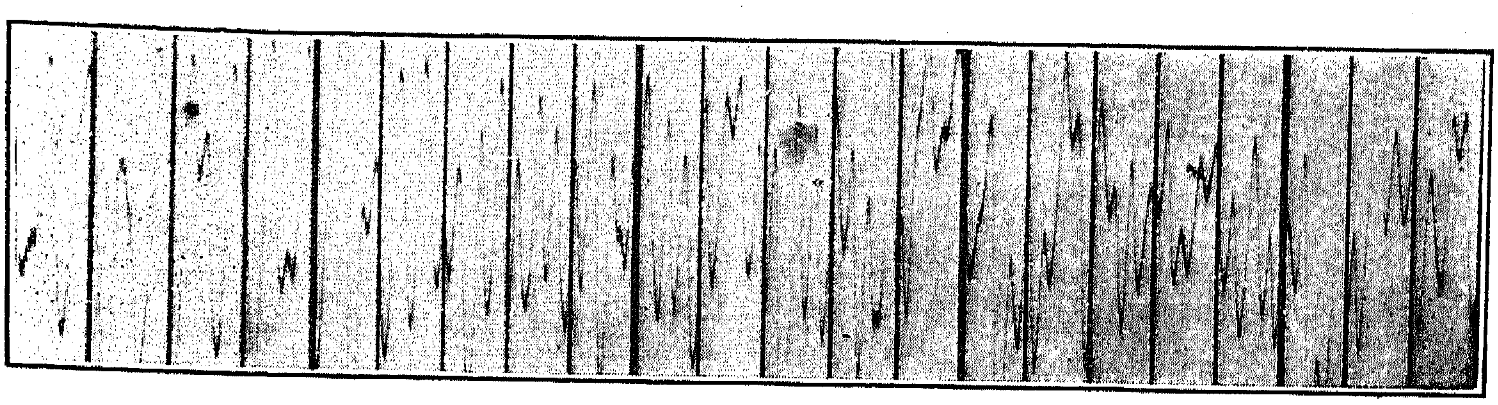
CURVE 8—g in gō

g in go, shows special pattern picture.



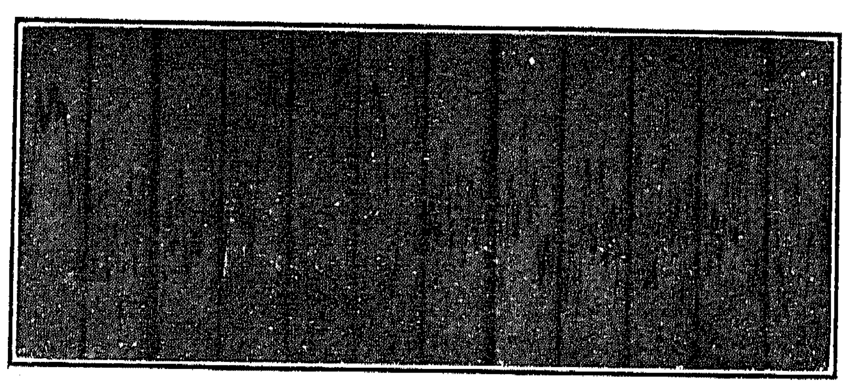
CURVE 9—h in hĭ

h in hi, shows special pattern picture. (Repeating).



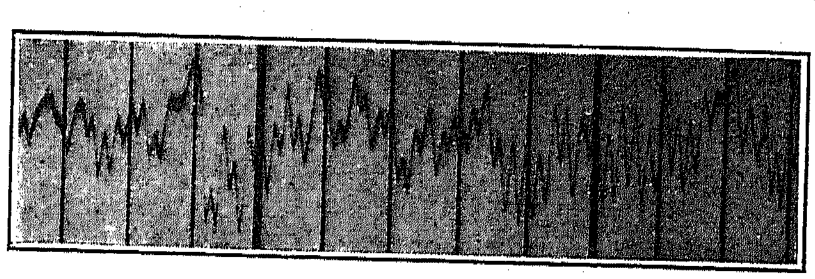
CURVE 10—ī in mī

ī shows 1700 cycles in special pattern picture. (Repeating).



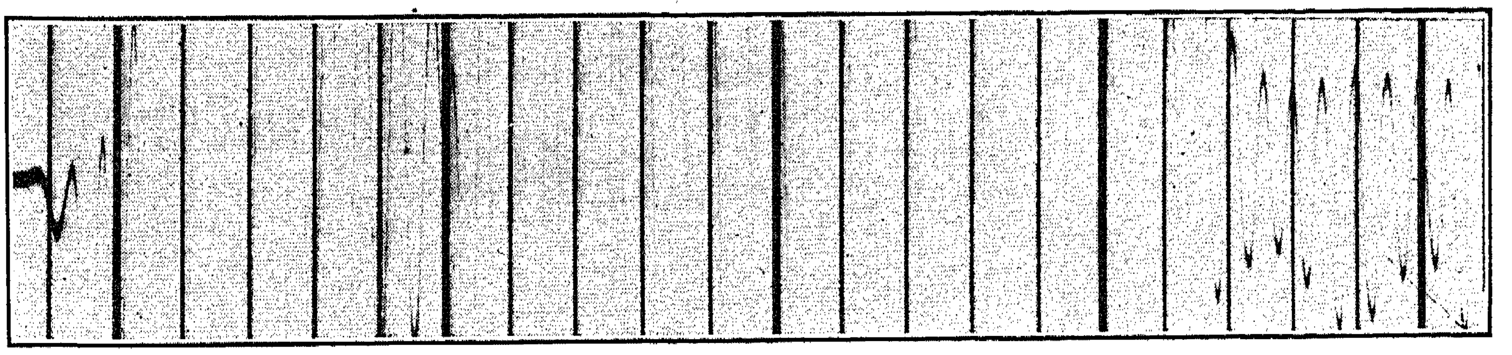
CURVE 11—ĭ in hĭ

í shows 2600 to 2700 cycles in special pattern picture. (Repeating).



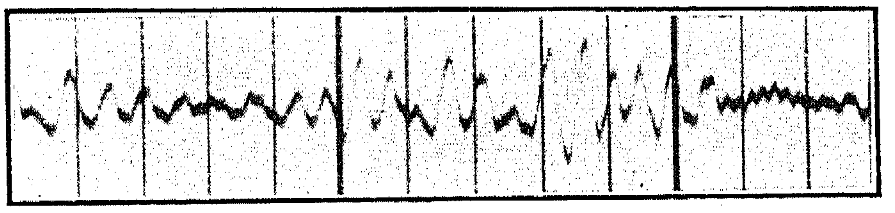
CURVE 12—j in Jōe

i shows 3000 cycles for 0.01 sec., 2500 cycles for 0.05 second, 2000 cycles for 0.01 second in special pattern picture.



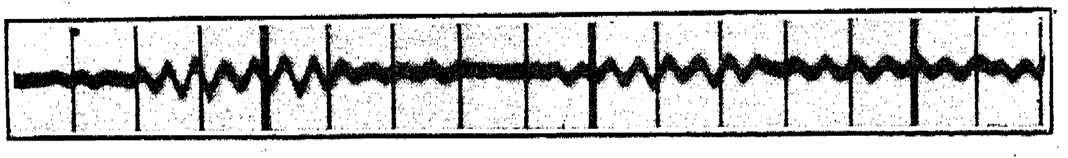
CURVE 13—k in kō

k shows special pattern picture.



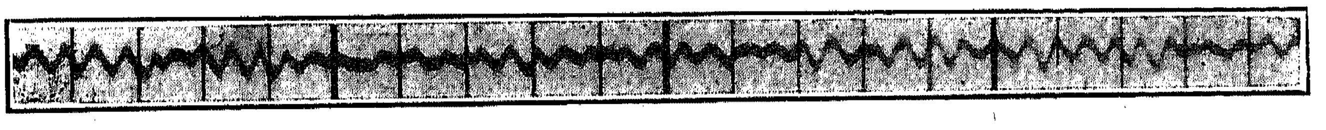
CURVE 14—l in lō

l shows alternation of 2500 and 1000 cycles per second in special pattern picture. (Repeating).



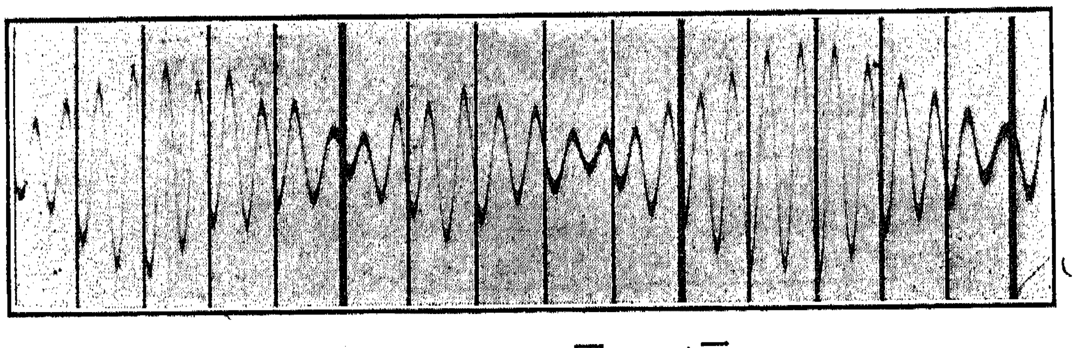
CURVE 15—m in mȳ

m shows 1200 cycles for 0.01 second, silence 0.006 second, 1200 cycles for 0.01 second in special pattern picture. (Repeating).



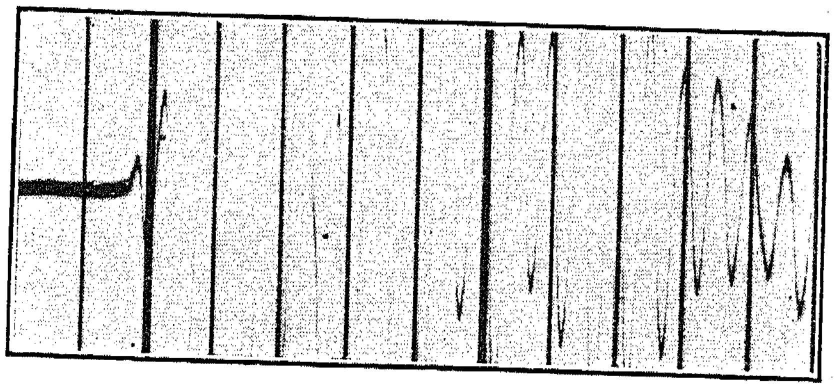
CURVE 16—n in nē

n shows 1100 cycles with silence following in special pattern picture. (Repeating).



CURVE 17—ō in tōe

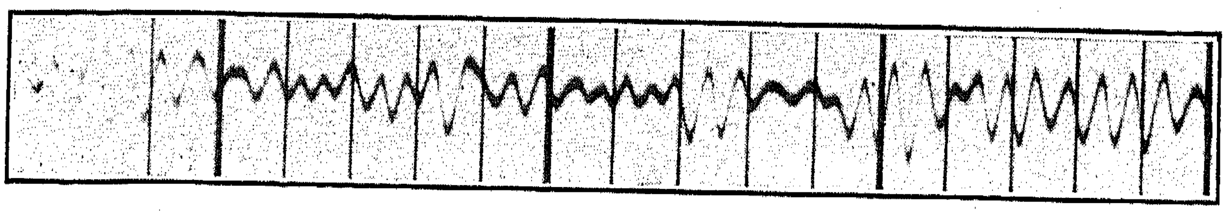
ō shows 1000 cycles in special pattern picture. (Repeating).



CURVE 18—p in pō

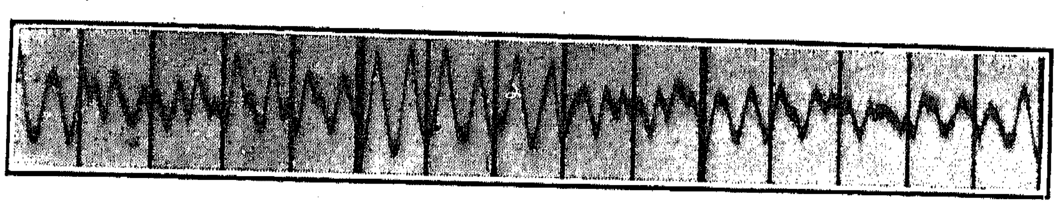
p shows special pattern picture.

q equals kyŭū.



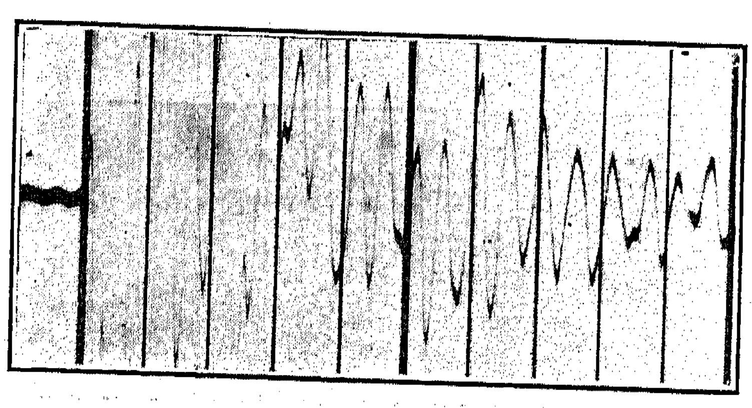
CURVE 19—r in rō

r shows alternation of 1000 and 1250 cycles in special pattern picture. (Repeating).



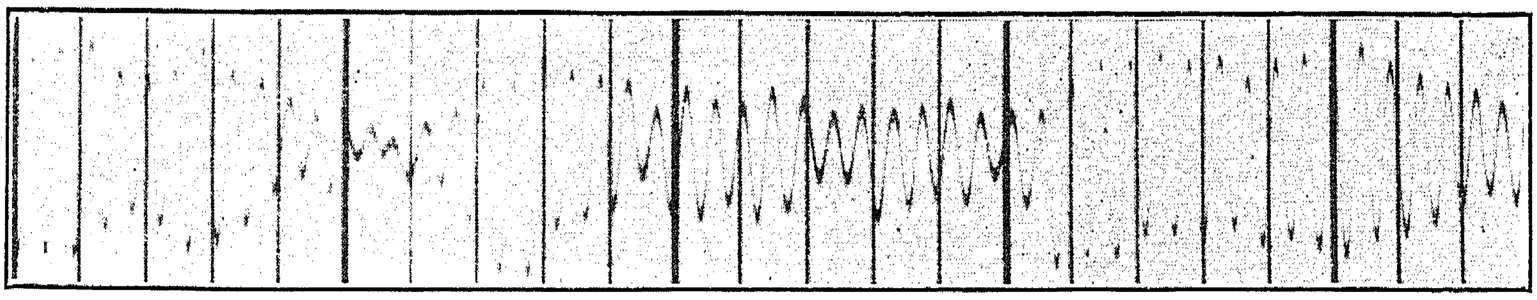
CURVE 20—s in say

s shows 1000 alternating with 2000 cycles per second superposed upon 1000 cycles per second. (Repeating).



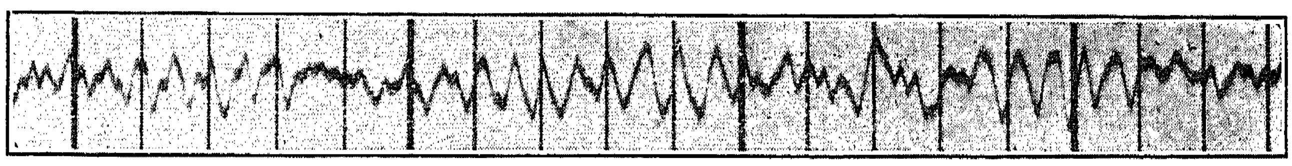
CURVE 21—t in tō

t shows special pattern picture.



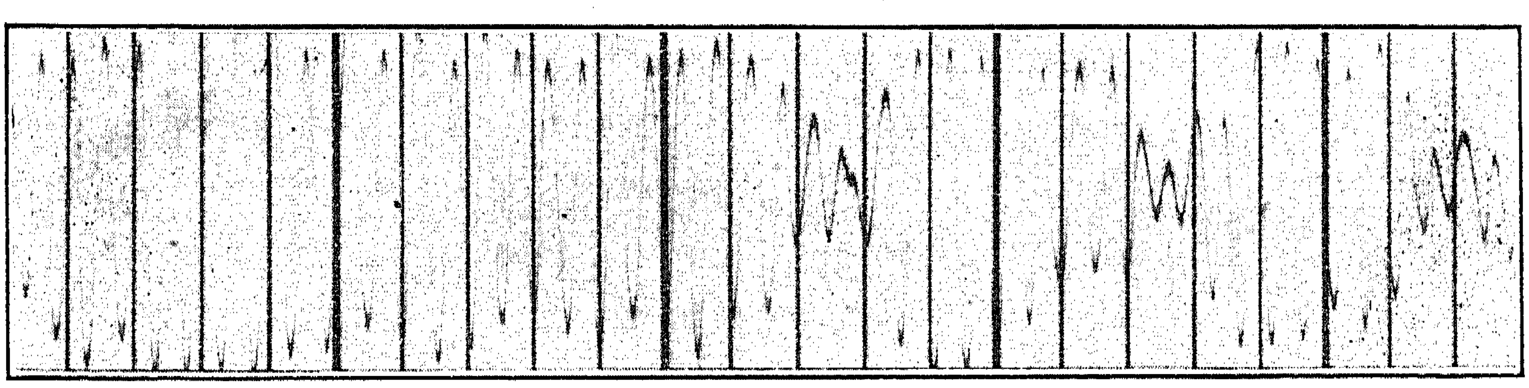
CURVE 22—ū in tū

ū shows 1100 cycles in special pattern picture. (Repeating).



CURVE 23—v in vē

v shows 1000 and 2500 cycles alternating in special pattern picture. (Repeating).



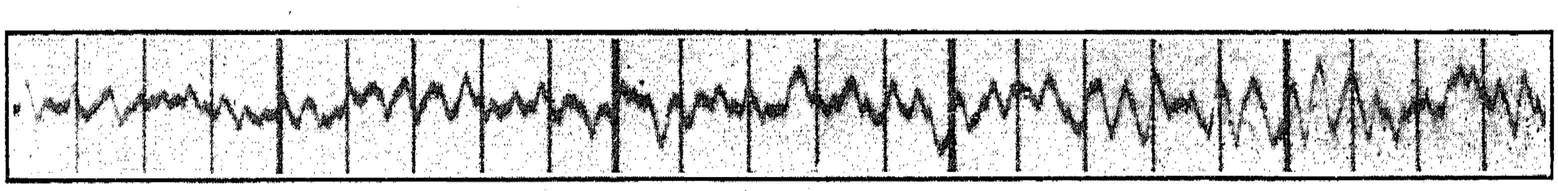
CURVE 24—ūō = w in wē

w in we, shows ū equals 1050 cycles; same special pattern as ū passing into ō equals 1000 cycles. (Repeating).

x equals ĕks

ȳ equals ū ī

y̆ equals ĭ



CURVE 25—z in zee

z shows 5000 and 2000 cycles per second alternating over 1000 cycles per second in special pattern picture. (Repeating).

From Helmholtz's formula for resonance of a spherical cavity with a small opening,

$$n = a\sqrt{\frac{3\,r}{8\pi^3 R^3}}\,,$$

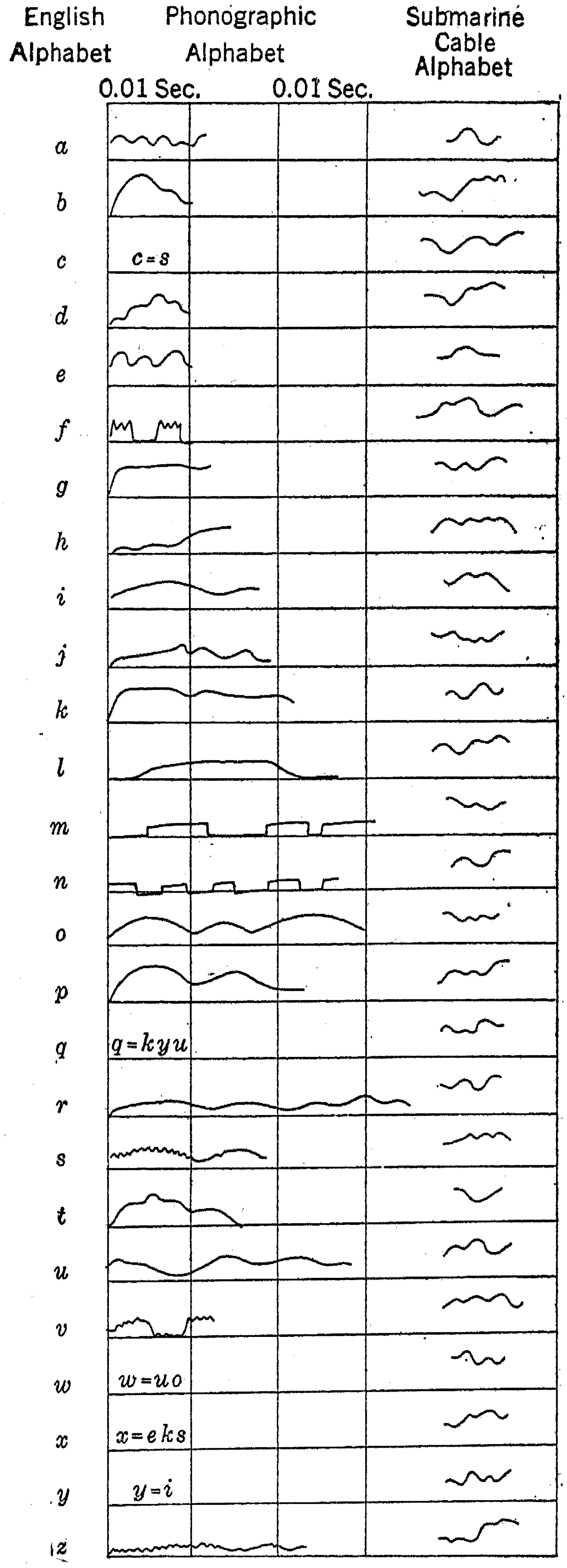
where n equals pitch of resonance of cavity,
r equals radius of opening of cavity,
R equals radius of cavity,
a equals 33,226 centimeters,

we can calculate the natural resonance tones of the mouth while uttering speech. I have done this and find that the resonance tones for the mouth vary from 800 to 3000 cycles per second, depending on the opening of the mouth. From our records, we find the pitches upon which whispered speech is uttered to be also from 1000 to 3000 cycles per second. This only shows, however, that pitch is an unavoidable characteristic of speech sounds. From the known facts, that a phonograph talking record may be run at more than twice the normal speed so that the speech tones must vary through more than a full octave and the speech is still quite intelligible, it is conclusive that pitch is not the main characteristic of speech sounds. That intensity variation is the main characteristic of speech sounds is well shown by the whispered speech records given, where no characteristic pitch is shown for b, d, g, k, p, t, but only definite pattern pictures. When the speed of the phonograph is increased, this pattern is shortened and distorted as we hear, but its main form is retained and we judge it as nearly the same as the sound at the correct speed and therefore are able to understand the speech. The pitch of speech sounds, then, only exists as a carrier of the speech-variations. In another paper not yet published on the Nature of Hearing and Perception, it is shown how pattern forms operate memory cells, and how we thus perceive the letter sounds of speech.

In general, the pattern form persists for at least 0.01 second and if the letter sound is sustained, the pattern repeats itself again and again. See pattern picture of letter ō sound, curve No. 17. One-hundredth second is the perception time. This is proved in the paper mentioned above. Therefore the mouth is a device for producing patterns of the necessary length and repeating them for sure perception.

Repetitions of pattern pictures of letter sounds (several times to make up a letter sound; see record of vowel ō, curve

No. 17,) are due to simultaneous excitatory and inhibitory action of impulses on same or opposing muscles in the mouth



or throat. At one moment excitatory impulse overbalances inhibitory impulse, then a maximum appears on the speech curve; when the excitatory and inhibitory impulses balance by interference (equal pull on muscle) no or little amplitude is shown on ō curve. "A slight and rapid muscle tremor is regularly produced by the simultaneous play of excitation and inhibition on one muscle, just as 'progression' and other rhythmic movements are regularly produced by the simultaneous play of excitation and inhibition on antagonistic muscle pairs. One muscle can actually receive excitatory and inhibitory influences simultaneously, and this condition results in a peculiar and characteristic muscle 'tremor'." (Sherrington C. S., "Nervous Rhythm," Proc. Roy. Soc., 1913, Ser. B, 86, 219-232; Forbes, A., "Reflex Rhythm induced by concurrent excitation and inhibition," Proc. Roy. Soc, 1912, Ser. B, 85, 289-298.)

The repeated use of patterns is the physiological basis of memory.

I conclude from an exhaustive search of 500 vowel and con-

sonant curves, that an accumulator or memory cell exists in the brain for each letter sound, detecting a definite picture

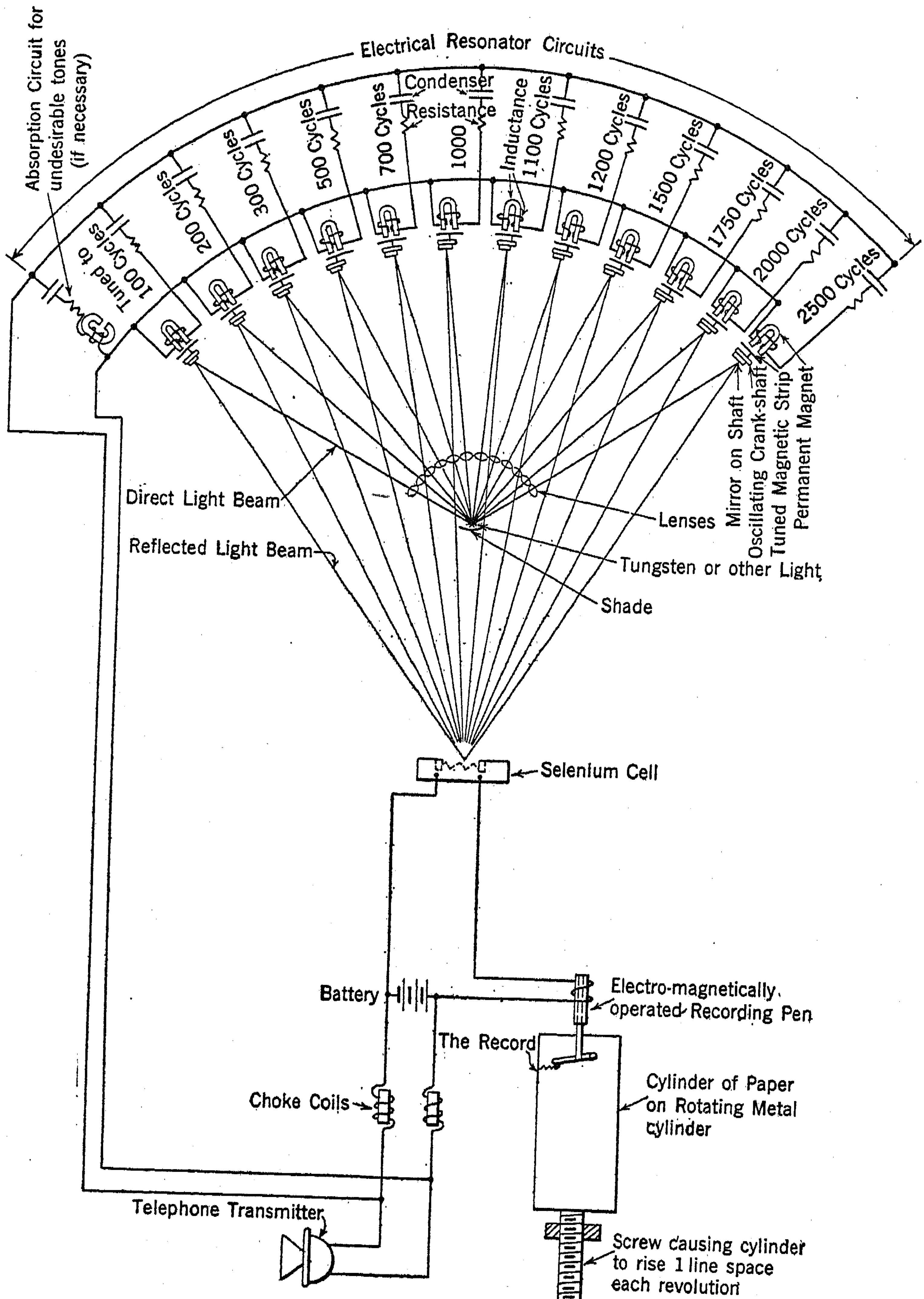
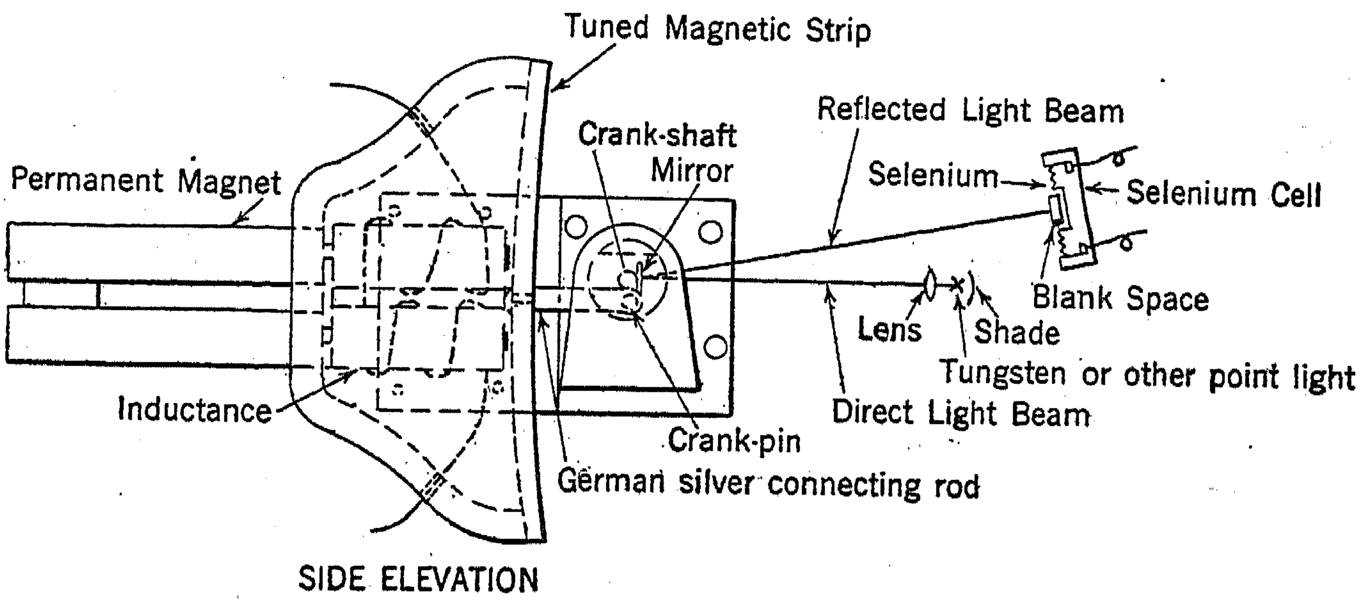


FIG. 1—GENERAL ARRANGEMENT AND WIRING DIAGRAM OF THE VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

pattern, such as that of the letter $\bar{o}$ which has a simple character of varying amplitudes, but repeats this character or picture pattern about 100 times a second. Since it takes 0.01 second

to perceive a picture pattern (perception time for sounds), this seems the right length of time (0.01 second) for a definite picture pattern to last and then to have repetition.

Having shown that speech is made up of a set of pattern pictures of sound waves called the phonographic alphabet, it seemed feasible to design and construct a machine which would record speech automatically in ink on paper in the form of this



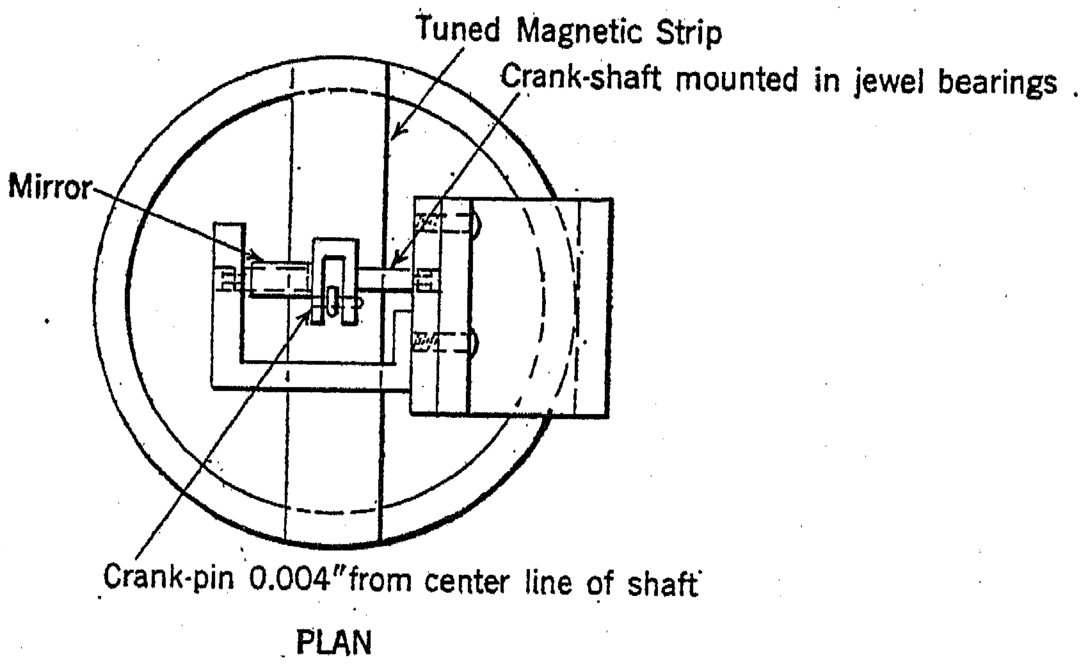


FIG. 2—MECHANICAL ARRANGEMENT OF MIRROR-MOVING MECHANISM OF THE VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

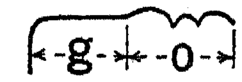
easily read compact system of natural characters called the phonographic alphabet. This machine has been carefully designed and will be completed in the near future.

VOICE-OPERATED PHONOGRAPHIC ALPHABET WRITING MACHINE

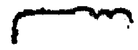
Fig. 1 shows a wiring diagram and general arrangement of the elements of this machine. Notation on the sketch explains the function of the different parts of the device. Fig. 2, in

plan and elevation, shows the mechanical arrangement of each electrical resonator circuit and how the resistance of the selenium cell is varied by the differences in the amount of light coming from the vibrating mirrors.

Method of Operation. On reference to Fig. 1, it is evident that by talking into the telephone transmitter, speech currents are caused to flow into the electrical resonator circuits. An audion may be used as a relay if desired, to increase the strength of the voice currents. That resonator which is tuned to the main tone of the speech at any instant, will respond, the current existing in it at any moment varying in strength according to the speech-variation. The magnetic strip placed over the poles of the electrical resonator magnet will vibrate powerfully (if the electrical tuning of the electrical circuit and the mechanical tuning of the magnetic strip are of the same tone as the tone of the speech). On reference to Fig. 2, it is seen that the vibrating magnetic strip causes the connecting rod to oscillate the tiny shaft held in jewel bearings. The connecting rod is pinned to the tiny shaft only 0.004 in. from the center line of the shaft. In this way, a motion of the magnetic strip of 0.0001 in. will cause angular motion of the tiny shaft of $1\frac{1}{2}$ degrees. A mirror fixed to this tiny shaft will oscillate with it and cause the beam of light from the tungsten or other lamp to be reflected onto the selenium cell. In the normal position of rest the mirror reflects the light beam onto a blank space at the middle of the selenium cell box where it has no effect on the selenium cell. When the reflected beam of light oscillates, both parts of the selenium cell on each side of the blank space will be illuminated and the resistance of the selenium will be decreased, allowing more current to pass through it from the battery and causing the electromagnetic recording pen to trace a wavy line on the paper sheet fastened to the revolving platen.

To illustrate the method of operation: Let the word "go" be spoken into the telephone transmitter. From our table of the letters of the phonographic alphabet we shall expect the recording pen to write "go" in the form of 

. It is known from my research that there are present in the sound of a man's speech, principal tones of 100 cycles per second (the fundamental tone of a man's voice), 200 cycles per second (the 1st overtone of the man's voice), and a tone of approximately 1000 cycles per second (the resonance tone of the mouth for the o-position.) These three tones will be moulded or varied in intensity simul-

taneously by the muscles of the throat and mouth, first in the g-form (a sudden explosion of the three tones) and then in the o-form (a quick waxing and waning of the three tones.) Three tuned electrical resonating circuits marked respectively 100, 200 and 1000 cycles will simultaneously respond to the three tones and three beams of light will oscillate over the face of the selenium cell, each vibrating after the same pattern at the same instant of time. The current in the selenium cell and in the recording-pen magnet will vary in strength, first according to the g and then to the o-form, causing the writing in ink on the rotating paper cylinder of  . In the same way, all letter sounds are written and we thus have a visible-writing machine recording our thoughts as rapidly as we speak, in the natural alphabet.

This work was conducted by cooperation of the Dept. of Physiology, College of Physicians and Surgeons, New York, and the Underwood Typewriter Co.

DISCUSSION ON "THE TRUE NATURE OF SPEECH" (FLOWERS), NEW YORK, FEB. 9, 1916

H. B. Williams: Mr. Flowers has made a definite and valuable contribution to the physiology of speech by showing that in whispered speech the vowel frequencies are very nearly the same for all adult individuals.

His theory that the peculiar curves he obtains at the beginning of spoken or whispered syllables where the first sound in a consonant is due to variations in intensity of the vowel sounds, is ingenious and interesting, but I believe the curves admit of a different interpretation. Such curves could undoubtedly be analyzed into a number of higher frequencies and the fact that in all of the curves of consonant sounds there are marked departures from the sine wave form lends color to the view that higher frequencies may be present.

To record all frequencies of a complicated sound in proper relative amplitude, the recording instrument should have a natural period higher than the highest component by at least one power of ten.

The galvanometer employed by Mr. Flowers for most of his work had a natural period not far from 250 and was critically damped. If the accessory apparatus was arranged so as to give satisfactory amplitude when this instrument was executing forced vibrations at the rate say of 2000, a rate of four or five times that would be almost entirely smoothed out. For this reason I think it unwise to draw too sweeping conclusions from records obtained by this method.

The experiment of running a phonograph at different speeds and securing clear articulation might be also explained by the assumption that the sound is recognized by the association of a number of frequencies which bear a definite relation to each other. No one, so far as I am aware, has ever assumed that the speech sounds were characterized by a definite absolute frequency.

L. T. Robinson: It seems to me in the paper now before us and in a great many previous writings, we have gone too far on the assumption that the electrical wave was the sound wave. There is enough difficulty, perhaps, in recording the electrical wave; but there is a tremendous difficulty, in my own mind, in making that leap from the sound wave to the electrical wave. I have done enough work in this line to convince myself that in most cases the sound wave and the electrical wave are quite different.

Albert C. Crehore: I have had some experience with the galvanometer which has made these records, for another kind of work, a study of the nerve transmission. Here the galvanometer is practically short circuited through the induction coil and for that reason the electromagnetic damping is very great.

In the case of the work I was doing, there are ten thousand, twenty thousand or thirty thousand ohms in a little section of the nerve that comes in so that it is a comparatively undamped vibration.

There is one thing which Mr. Flower's work has almost established, and that is where he has differentiated between whispered speech and speech involving the vocal chords. The consistency obtained in these curves for whispered speech in different individuals, whether male or female, is very striking, and there must be some foundation for it. I do not mean to have you understand that the curves which are here given represent accurately the current or the sound wave necessarily. Whether they do or not, you can compare the consistency of them—I mean to say if under similar conditions, you have a constant result, it has a meaning irrespective of the fact whether it is a true record or not. In using such a galvanometer we always take the control, that is, place a known potential suddenly across the terminals and observe the deflection and time record. This is invariably done during the course of any work with the galvanometer, because you can change the tension of the string at a moment's notice. I would like to see a control curve showing the condition of the galvanometer for these records. I assume that the string was slack and had a very low period of vibration, necessarily, because there is not sufficient energy to get results otherwise. But under these conditions we are recording forces or vibrations with a string which is absolutely damped, and there would be no over-shooting of the string if you should deflect it. Imagine the string at the top point of any one of the curves, where the force suddenly reverses; if the same force had been left on indefinitely, the curve would have risen up far beyond its base, so that it is not a true record of the force that is there at any given moment if we calibrate the instrument with direct currents. The average force is practically zero, and so you have a wandering zero. I do not think that detracts to any material extent from the deductions you can make from the records, even though the curve which Mr. Flowers gives as an alphabet may have to be modified.

William Maver, Jr.: In Dr. William Hanna Thompson's work "Brain and Personality," in debating the manner in which the nerves and muscles of the body are trained and controlled, he remarks that certain instances to which he has referred of highly trained muscles cannot be compared for complexity and difficulty with the training of the muscular organ, the tongue, for the movements necessary for articulate speech. An animated orator, he adds, has to make a greater number of rapidly succeeding and yet perfectly adjusted contractions and relaxations of his muscles of articulation than any famous performer on a musical instrument. Mr. Flowers apparently has accomplished the difficult feat of photographing the rapidly varying vibrations due to these rapid yet perfectly adjusted contractions and relaxations of the muscles of articulation.

In accord with other writers on the general subject of the fixation of knowledge in the brain, Mr. Flowers expresses his belief that a particular brain cell receives the impression of a given pattern picture. In this relation, Mr. Flowers later points out that when one becomes familiar with the phonographic alphabet he will be able to read it as easily and as intelligently as the telegraph operator reads the signals used in submarine telegraphy.

We might find an analogy to the view that particular brain cells respond to given pattern pictures in the case of certain printing telegraph systems. For instance, the Baudot system, much used in Europe. In this system combinations of five pulsations of positive and negative current are transmitted over the wire for the letter of the alphabet, a different combination for each letter. According to the manner in which these pulsations of current arrive, certain relays will be operated, and these relays in turn will select the letter represented by a given combination of pulsations, by bringing the desired letter on a typewheel opposite a paper strip, on which the letter is immediately printed. This is termed in the art, selective printing telegraphy.

As a matter of interest, it is quite as accurate to say that the Morse telegraph is also a selective system of telegraphy, whether the signals transmitted by that system are received on a paper strip as dots or dashes, or by audible dots and dashes, so-called. In receiving messages by sound, the ear transmits the combinations of dots and dashes representing given letters of the alphabet to the brain cells that have been trained for this purpose, so-called memory cells, and the brain cells concerned respond to the given combination of signals, and we or the something within us which I think Dr. Thompson would term our personality, recognizes the signal for what it is meant. Correspondingly, the trained brain cells, or as we would say in telegraph phraseology, the properly adjusted brain cells, which receive through the eye their impressions of Mr. Flowers' phonographic alphabet, respond by vibrating or otherwise in such manner that again our personality recognizes the impressions for what they are meant.

Perhaps for the purpose of assisting in illustrating the foregoing, we can utilize Fig. 1 in Mr. Flower's paper. Let us consider the tuned electromagnets in the diagram as the equivalent of the memory cells of the brain which have been attuned or adjusted to special rates of vibration, or otherwise suitably adjusted, by frequent visual repetition of the pattern pictures. Now, whether the memory cells when stimulated by the pattern picture are the equivalent of a selenium cell or the equivalent of an electrically operated recording pen for the interpretation, deponent saith not. Perhaps Mr. Flowers will have some enlightenment for us on this subject in his forthcoming paper on the nature of hearing and perception.

William J. Hammer: Regarding Mr. Flowers application of the selenium cell in his work, permit me to say that while people

with limited experience ridicule the employment of the selenium cell because of its unreliability, its inertia, etc., I wish to say that I have frequently demonstrated its reliability, and some of its many practical applications, were shown before the Institute at its joint meeting with the American Electrochemical Society on April 17th, 1903 during my lecture on "Radium, Selenium, etc.", at which time I operated 5-h.p. motors and generators, fired cannon, turned lights on and off, talked over a beam of light, etc., by means of selenium cells and an acetylene lamp, and the proper relays and switches.

As illustrating in a remarkable manner the sensitiveness of the selenium cell to sound recording reproductions and transmission, I beg to call the members' attention to Mr. Ernest Ruhmers photographophone which I described at my lecture in 1903, and which I personally operated in Berlin in 1902.

In these extraordinary experiments, when one talked in a telephone transmitter connected in a shunt circuit of an arc lamp it caused the light to vary as a manometric flame. The light beams were passed through a cylindrical lens in the front of a moving picture camera and photographed in striations of varying width and intensity upon the moving film. After the film was developed and put back into the box and the arc lamps replaced (but now burning steadily) the striations on the film acted like slats in a shutter to allow more or less light to pass through the film and to then fall upon a selenium cell in the back of the box. To this cell a pair of telephone receivers was connected, through the intermediary of which the original message could be distinctly heard.

Let me further remind the members of the comparatively recent and entirely successful transmission of pictures through the intermediary of the selenium cell, from Paris to London, across the English Channel, the pictures appearing in the London papers within a few hours.

L. W. Chubb: I have made some tests to check some of the present theories of speech and vowel sounds. The theory of constant frequency and mouth resonance for vowel sounds, was disproved both by the phonograph test, also tried by Mr. Flowers and by the singing of vowels at a note of higher fundamental frequency than the supposed frequency of the vowel. As an example the vowel "oo" is supposed to be represented by the resonance or amplification of harmonic frequencies around 400 cycles per second, and yet the vowel or a word containing it could be distinguished when sung several notes above high C.

The results of such tests and the disagreement between spoken and whispered vowel sound waves, makes me feel that the resonance at constant frequency, although present, is not the distinguishing feature of the sound.

Is it not possible that Mr. Flowers' pattern theory is correct and that the resonance of certain frequencies in certain sounds, is unconsciously produced by the speaker so as to combine adja-

cent harmonic components in such a way as to get a low frequency pattern or beat?

Comfort A. Adams: Dr. Kennelly has done a large amount of work, both theoretically and experimentally, in analyzing the connection between the vibration of a telephone receiver diaphram and the current producing it, as well as the relation of the deflection of an oscillograph system to the current producing it, over a wide range of frequencies. On the oscillograph end of this work, in which I have been much interested, we have found that the record is fairly accurate up to within a comparatively small percentage of resonance. That is, there must be no appreciable harmonics of that order in the current being measured. Theoretically the problem is extremely difficult when all the numerous variables are considered, but fairly reliable results can be obtained, when the limitations of the instrument are appreciated. Otherwise it is very easy to be badly misled by oscillograph records.

A. C. Crehore: In my remarks upon Mr. Flowers' paper, I had in mind chiefly the application of the string galvanometer for recording such waves as are shown in the illustrations in the paper. It seemed inopportune to introduce a theoretical discussion of the galvanometer in connection with this paper merely because I have worked out the theory of it. There is a great deal to be said about it and of a very complex nature. We have to study nothing less than the complex motions of a stretched string. Think of it, if you please, as a violin string set in motion not by the bow acting at a single point of the string, but by the magnetic field distributed in some way along most of the length of the string, the force thus being applied to many parts of the string simultaneously and in varying amounts, and we have a partial statement of the problem to be solved.

So, in my remarks, I had hoped that you would accept the statement as given without proofs that the movement of the string under the conditions imposed by Mr. Flowers' problem could not possibly be an exact reproduction either of the waves of sound or of the current in the string, but it might approximate it closely if the conditions were properly met. To have emphasized this point at some length by these proofs would have seemed to detract from the merits of Mr. Flowers' findings, for I believe it to be feasible to obtain results of some value with an instrument which does not record the exact sound waves but yet shows much valuable detail, as this instrument does. We may be assured that if similar results are obtained on the films in different instances the probability is very strong that similar sound-waves caused the records to be alike. This is where I think Mr. Flowers has made a real contribution to our knowledge.

It is my conviction that the records are at best approximations with all existing instruments and this is the reason that a theory of the instruments, is so much to be desired. It tells why the records are approximations and what must be done to make the approximation closer.

The way in which the magnetic field is distributed along the length of the string is of prime importance in the resulting motions of the string. In instruments as now constructed this field is uniform as nearly as this condition can be readily obtained over nearly the entire length of the string. If the field were exactly uniform the proof is very simple that the curve assumed by the string is the arc of a circle under the action of a steady direct current, no matter how great the deflection. This fact gives rise to certain complex motions of the string, each corresponding to the terms of a Fourier series expressing this circular arc, that is, when variable currents are applied. The simplest possible manner of the field distribution along the string, so far as the resulting motion of the string is concerned, is that of a sine-curve, the field strength being a maximum at the center and tapering according to the sine law towards both ends. With such a field the curve assumed by the string under the action of a direct current is also that of a curve of sines, which, therefore, is expressible by the first term only of a Fourier series. The motions of the string under these conditions are the simplest possible, and the complete solution of the motion of the string, for any kind of a current is known. This solution is complex enough, to be sure, but it is safe to use this solution as a basis for making certain deductions, and if it is apparent in this simpler case that the string can not follow exactly such sound waves as Mr. Flowers applies to it, so much the more would this be true for the more complex solution in the ordinary case of uniform field distribution. This solution in the case of the sine-wave distribution of the field for a simple harmonic e. m. f.

$$e = E_1 \cos \omega_1 t = f(t) \tag{1}$$

is, for the periodic portion of the motion alone,

$$y_1 = \frac{H_0 E}{\rho R} \frac{\cos(\omega_1 t - \epsilon_1)}{[(n_1^2 - \omega_1^2)^2 + k_1^2 \omega_1^2]^{\frac{1}{2}}} \sin \frac{\pi x}{l}, \tag{2}$$

where y is the deflection of any element of the string at the distance x from one end of it, and l the length of the string. H_0 is the strength of the magnetic field at its maximum point in the center of the string, ρ the mass of the string per unit of length, and R the total resistance of the circuit, in which the inductance is supposed to be negligible. These and the other quantities in this equation except t are constants, and the equation gives the motion of the string as a function of the time. The phase angle ϵ, is such that

$$\tan \epsilon_1 = \frac{k_1 \omega_1}{n_1^2 - \omega_1^2}, \tag{3}$$

and the constants n_1 and k_1 in terms of the properties of the string and the air damping factor k are

$$n_1 = \frac{\pi}{l} \sqrt{\frac{T_1}{\rho}} \tag{4}$$

and

$$k_1 = k + \frac{H_0^2\, l}{2\,\rho\, R} \tag{5}$$

When the e. m. f. is a complex function of the time, it is expressible as a Fourier series of cosine terms, and the resulting complex motion of the string is then merely the sum of a series of terms, each similar to (**2**) in which ω_1 and ϵ_1 take different values, all other quantities remaining the same as before. An easy way to see these results is by means of specific examples, illustrated as curves. Since the observations on the string are

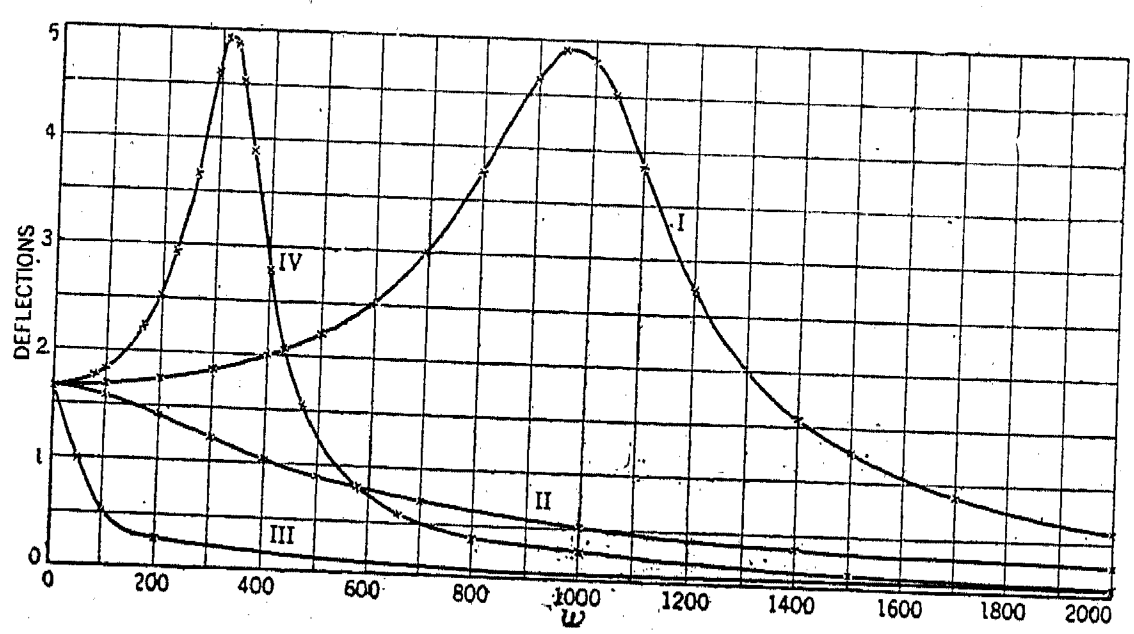


FIG. 1

usually made at its central point, where $x = l/2$, we may first simplify (**2**) above by making $\sin \frac{\pi x}{l} = 1$, and writing y_0 for y, this meaning the deflection of the center of the string. The curves that are instructive are the relations between the deflections of the string produced per unit of current as the frequency alone varies, keeping the resistance of the circuit constant. Curve I, Fig. 1, is such a curve plotted from (**2**), showing an increase in the deflection per ampere up to a critical frequency of $\frac{1000}{2\pi}$, and then rapidly falling off for a further increase. The character of this curve is much affected by the particular resistance originally assigned, and the resonance effect is more pronounced the greater the resistance. Curve II represents the same thing, the only difference being that the resistance originally chosen for the circuit is one-tenth of previous value and the impressed volts also one-tenth, the current being the same. Curve III

shows a further decrease to a one-tenth value in the resistance and volts, the current being the same in the three curves. The resonance effect has entirely disappeared in these latter two curves. From (**2**) the maximum value of the deflection may be written

$$Y_1 = \frac{Y_0}{[(n_1^2 - \omega_1^2)^2 + k_1^2\ \omega_1^2]^{\frac{1}{2}}}\ , \text{ where } Y_0 = \frac{H_0 E}{\rho R} \qquad (\mathbf{6})$$

or at the critical frequency, when $n_1 = \omega_1$, this is simplified to

$$Y_1 = \frac{Y_0}{k_1\ \omega_1} = \frac{H_0\ E}{\rho\ R\ \omega_1 \left(k + \dfrac{H_0^2\ l}{2\ \rho\ R}\right)} \qquad (\mathbf{7})$$

And if the damping factor $\dfrac{H_0^2\ l}{2\ \rho\ R}$ is small compared with the

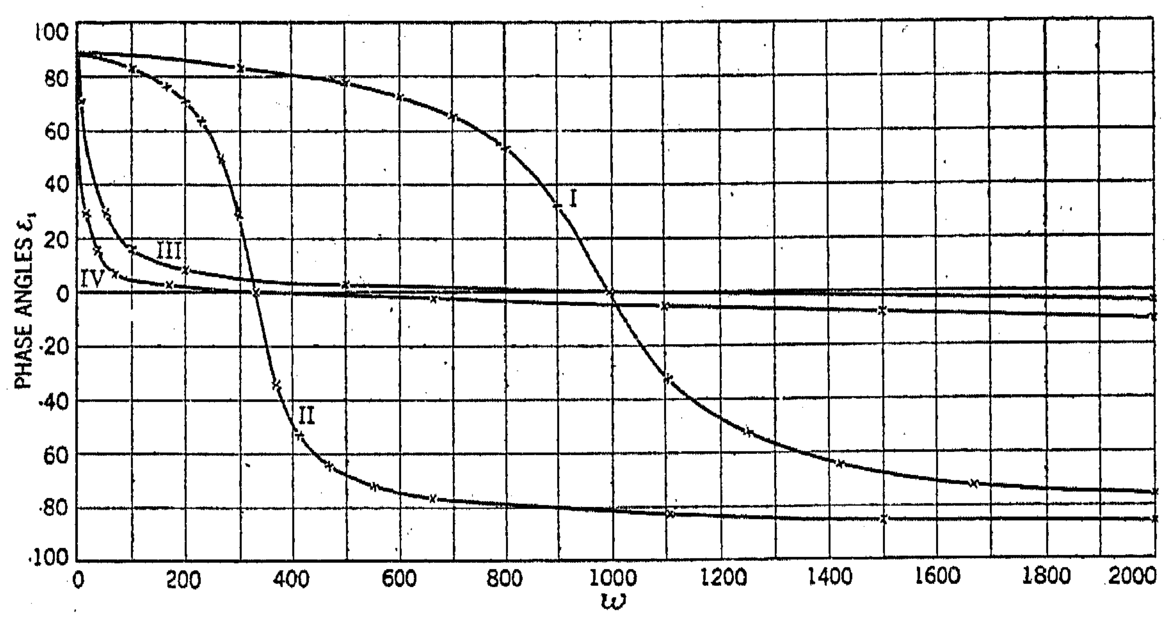


FIG. 2

quantity k, the air damping factor, the deflection at this critical frequency with the same current and frequency is almost exactly inversely as the resistance of the circuit, as is evident in these three curves.

If the value of n_1 is reduced to one third of its value for these three curves by increasing the tension on the string, we would get a curve like IV for the same resistance in circuit as that in Curve I. This shows a much sharper resonance point. The voltage and current for this curve are, however, increased so as to give the same deflection for a direct current or a zero frequency.

Another set of instructive curves are those showing the changes in the phase angle ϵ_1 (**3**) with a change in the frequency, other things remaining unchanged. Some of these are shown in Fig. 2, Curve I being that corresponding to Curve I of Fig. 1, where the critical frequency is such that $\omega_1 = 1000$, and resistance the same as in that curve. A decrease in the resistance alone will change this curve into one like Curve II. Curves III and IV are a similar pair for the case of greater string tension, III cor-

responding to IV in Fig. 1. The phase angle is zero in each case at the critical frequency, and changes from 90° at zero frequency through zero, to approach $-90°$ at very great frequencies.

We now come to the consideration of the case that applies to the condition of the galvanometer in Mr. Flower's records. The frequencies that he records are far above the critical frequency, which is determined by the string tension, and we are then working at a point on the curves at some distance to the right of the peaks of the deflection curves in Fig. 1. If we had to deal with a single sine-wave voltage alone of varying intensity and definite frequency, the record would give deflections strictly proportional to this voltage, but if the frequency decreased we would get a slightly different deflection for the same voltage. The fact, however, that these curves may change very slowly in height with an increase of frequency when we are far removed from the critical frequency goes to show that the approximation to proportionality may be fairly close over a certain range of frequencies, although it can never be exact.

Similarly the phase angle also may remain fairly constant over a certain range, but this phase angle does not make much difference if we only have to record a single-sine-wave. The making of the record is merely delayed a constant fraction of a cycle behind the current in the string. It is when two or more harmonic forces, that go to make up the complex waves with which we are concerned, are present simultaneously that the phase angle or the time lag becomes important. To illustrate the case suppose there are but two waves and the one double the frequency of the other. The phase lag of each may be very large for high frequencies approaching 90°. This would mean that the absolute shift in time would be twice as much for the slower wave as for the faster, and that their relative shift amounts to one quarter cycle of the higher frequency wave. If the original waves coincided in phase, the zeros of the higher frequency coming at the zeros and the maxima of the slower wave, they never would so coincide in the record, but the zeros of the lower frequency would come at the maxima of the higher frequency. This condition would not give anything like a true record of the original, but it might answer some purposes if one were studying one particular frequency.

Curve II, Fig. 2 shows, however, that this phase lag may not only be fairly constant over a considerable range but that it may also be zero over this range as well. In this condition the relative phases are not displaced and the record should approach quite closely the current in the string in form with the understanding that all the lower frequency waves are magnified in amplitude a little more than the higher ones. So we see that it is possible with a string galvanometer to record a complex wave in an approximately correct form but only approximate. It is evident, also, from the preceding remarks that it will not

do to calibrate this galvanometer by means of a direct current, and expect that for each deflection observed in the high frequency record the current is the same as that due to a direct current of the same intensity. Curve III, Fig. 1 shows this. The current is the same throughout this curve, and the small deflection at the high frequencies is in great contrast to the large one at the origin where the current is steady. If at any point of the record save where the current is zero one should suddenly maintain the current then existing, fixed, the deflection of the string would in general go way out of the field, becoming very large. If, however, you are so well acquainted with your instrument as to know its constants and exactly what you are doing, the calibration with direct currents together with the use of a theory will give the deflections to be expected at any frequency.

I have illustrated this subject by the use of an ideal string galvanometer, the like of which does not exist, and have shown that we may only hope to get a fairly close approximation in any case to the current in the string, and have not said anything about the phase shifting effects of the induction coil and telephone transmitter as being beyond the scope of my remarks. If we should employ an actual string galvanometer, whose magnetic field is approximately uniform throughout the string, the approximation would not be so close as that obtained with this one. In skilled hands this instrument is capable of giving results that can be relied upon, but it is important to know its constants, and to understand the theory of it in order to arrive at those conditions which will give the closest approximation to any desired result. When there is a complete knowledge of these things it is possible to apply the theory to certain records, and correct the records to give the probable true currents in the string.

The curves which I have used to illustrate my remarks are not those which apply directly to the condition of the galvanometer as Mr. Flowers has used it. In his case the electromagnetic damping is the larger of the two, and in these curves I have supposed that the air damping is the greater.

J. B. Taylor: This paper may be discussed from several different points of view:

First, the connection between the nature of speech and electrical engineering.

Second, the correctness of the photographic records offered, as representing the form of the associated sound wave.

Third, the correctness and originality of the theory favored by the author based on these photographic records or on his other data.

Fourth, assuming the theory to be correct, how closely may the author's "pattern pictures" for the alphabet from *A* to *Z* be taken to represent the true patterns?

Fifth, can a voice-operated machine be made along the lines described to write definite, readable characters when spoken into?

The nature of speech is quite as proper a subject for consideration by electrical engineers as any of the problems of telephony, since for perfect speech transmission, there must be exact correspondence between the sound waves produced by the complex actions of the speech mechanism, the mechanical motions of telephone apparatus and also of the transmitted current as modified by resistance, reactance, capacity, permeability and hysteresis of iron, etc. Theoretical and practical difficulties all along the line prevent perfect sound transmission. The telephone user, conversing easily day after day, often fails to realize the dependence which is placed on context and is at a loss to explain the difficulty of understanding proper names, figures and unfamiliar words. Note the changes which have been made in telephone call letters in the attempt to reduce mistakes, and the special telephone language which is springing up to further assist in this direction. Any attempt to improve telephone apparatus and transmission or transformation conditions must have as foundation, knowledge of the essence of speech and a knowledge of the relative importance of the different factors, so that where compromise must be made, the more necessary speech factors will be the least disturbed. These remarks apply as well to "loud-speaking" telephones for train announcing and similar uses, and perhaps with even more force, to the rapidly developing field of radio-telephony where many new devices and remarkable transformations are brought into play.

Regarding the photographic records, it should be borne in mind that these were made with the help of a string galvanometer. While this has high current sensibility, as compared with an oscillograph, its natural period is perhaps 300 or 400 per second against the figures 6000 to 10,000 for the oscillograph. This would call for some correction on all of the curves, and indicate markedly different appearance in those, such as numbers 3, 6, 7, 11, 12, 14, 20, 23 and 25, where the author assigns frequencies of 2000 to 3000 cycles and in the last case up to 5000 cycles per second. No mention is made of the natural frequency of the acousticon transmitter and diaphragm with its connected parts and closely associated air cavity. In my study of sounds and telephone currents with the oscillograph, I have found the form and adjustment of the transmitter, a highly variable factor in the resulting record. For example, in A.I.E.E. TRANSACTIONS, Vol. XXVIII, 1909, Part II, page 1169 oscillograms are shown, made with different transmitters. Though the records differ greatly in appearance, the inexpert telephone user would probably notice no difference in the receiver.

Bearing on this criticism, Mr. Flowers has replied that the correctness of his records was checked by constructing a selenium cell phonograph and that the reproduced sound was distinguished as being the same vowel or consonant originally uttered. Such a test I believe shows merely that much liberty can be taken with the shape of a sound wave, as is actually done with the

regular telephone, and still have recognizable speech. I base this statement principally on some tests in which several tandem conversions were made from electric current to sound, back to current and again to sound, with oscillograph examination at the different stages.

Many experimenters and observers have studied the nature of speech and numerous devices have been employed to analyze or record the sound wave. We may mention the phonautograph of Leon Scott, spherical rèsonators, sensitive flames, diaphragms arranged to deflect a beam of light, diaphragms set up as part of an interferometer, motion of soap films, study of telephone currents by resonant circuits, oscillograph or string galvanometer and by microscopic examination or enlarged transcribing of phonograph records.

Following some of the theories as to the nature of speech offered as a result of these studies and also by independent cut-and-try methods, various attempts have been made to construct machines which under proper manipulation would talk or at least produce one or more of the speech vowel tones.

As regards the consonants, it is quite generally agreed that these are not properly sounds but merely different fashions of beginning or ending certain other sounds. The very name itself, *consonant*, indicates that it is something that goes along *with* the sound rather than being *sonant*, or a sound of itself. Of all the possible speech sounds, there are of course many which are neither definitely vowel nor consonant in character. Mr. Flowers quotes Helmholtz to this effect on the second page of his paper and as far as the consonants are concerned, his records and conclusions appear to be in agreement with the generally accepted view.

The theory of speech, however, about which there has been and still is a pronounced difference of opinion, relates to the vowel sounds and here opinion has been principally divided between what is called the "harmonic" theory and the "absolute pitch" theory.

According to the harmonic theory, one vowel is distinguished from another in the same way as are two different styles of organ pipes, by the number and relative magnitude of partials consisting of fundamental and harmonic over-tones. To demonstrate the correctness of this theory, elaborate sets of electrically operated tuning forks with associated resonators, for controlling intensity of sound sent out from each, have been constructed. Although a great range of tone quality can be produced with such a set of resonators, personally I have never witnessed the apparatus manipulated so as to produce anything fairly approaching a speech vowel. Nor could I produce any of the vowels from a more complete apparatus, consisting of a number of electrical generators in harmonic series with arrangements for controlling the intensity of each.

In the early analysis of speech, it was found that certain

resonators responded readily to a given vowel tone, more or less irrespective of the pitch of a speaker's or singer's voice. This fact coupled with unsatisfactory results obtained from the series of harmonic forks, brought many adherents to the absolute pitch theory. If pitch alone were the essence of vowels, they should be heard frequently from a pipe-organ or from an orchestra. Such, however, is not the case. I have made phonograph tests (similar to that cited by Mr. Flowers) some years ago and agree with his conclusions on this point. Incidentally and as indicating the great caution which must be taken when using the phonograph to determine the essence of speech or study the quality of a sound, I may mention that Professor D. C. Miller several years ago, at the Cleveland meeting of the American Association for the Advancement of Science, operated a phonograph at normal and at reduced speed to show his audience that one vowel would change into another—in other words to show the correctness of the "fixed" or absolute pitch theory, the indentical experiment which Mr. Flowers cites to demonstrate the incorrectness of the same theory. The difficulty lies in too much psychology in proportion to the amount of physics. Having reason to doubt the sufficiency of either of the prevailing theories, or both in combination, I attempted to get at the root of the matter by observing and recording telephone currents with an oscillograph. The first of these records was taken in 1904 and the reproduction of a telephone current appearing on page 212 of Vol. XXIV of the A. I. E. E. TRANSACTIONS for 1905, is the earliest publication of such a record that I am aware of.

My records are not closely comparable to those in Mr. Flowers's paper for reason that he has limited his discussion to whispered sounds, whereas I gave attention principally to the sustained open vowels. Of these, the starting point is naturally the *A* (as in f*a*r.) This is the vowel which is produced by the voice mechanism with the muscles in the normal or relaxed position. It is the vowel on which the baby naturally cries, and it is extensively used in our vocabulary, as also in that of every other language. This sound however, does not appear among Mr. Flower's photographs nor in his alphabet of pattern pictures. This is because our alphabet is largely a series of arbitrary names for certain written or printed characters which in turn, in use may have any one of several different sounds. A more complete phonetic alphabet would have instead of 26 letters, approximately twice as many sounds of which, without going into the fine shades of pronunciation, some 14 or 15 would take the place of the present 5 character names for the open vowels.

I have previously described the sound *A* (as in far) as consisting of a series of relatively high frequency vibrations following a "curve of intensity." In the case of my own voice the vibrations proper come at the rate of 720 per second with an intensity cycle following a fairly definite curve at the rate of around 100 per second. The 720 cycles are subject to little or no control, while the 100

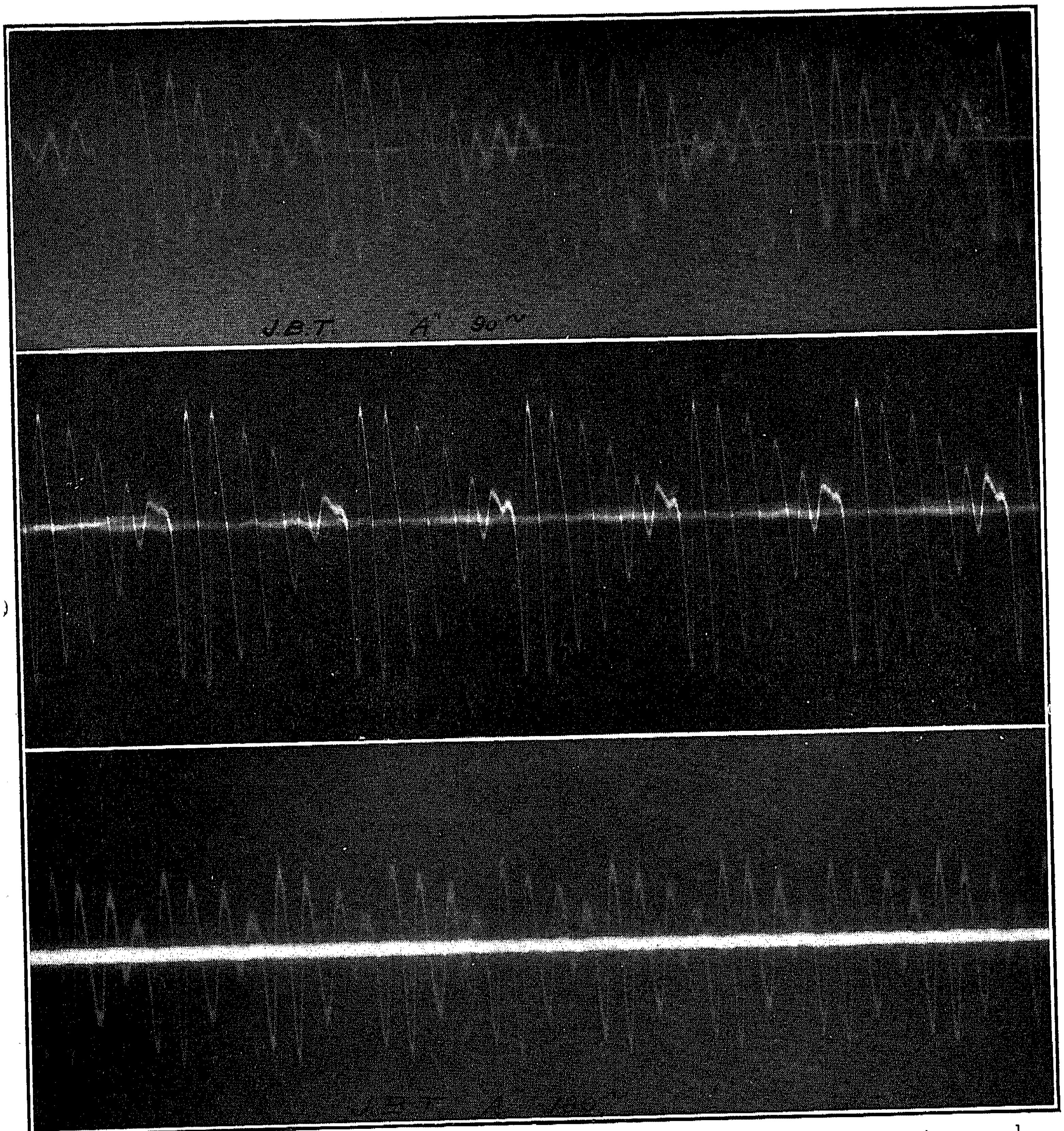


FIG. 3 [TAYLOR]

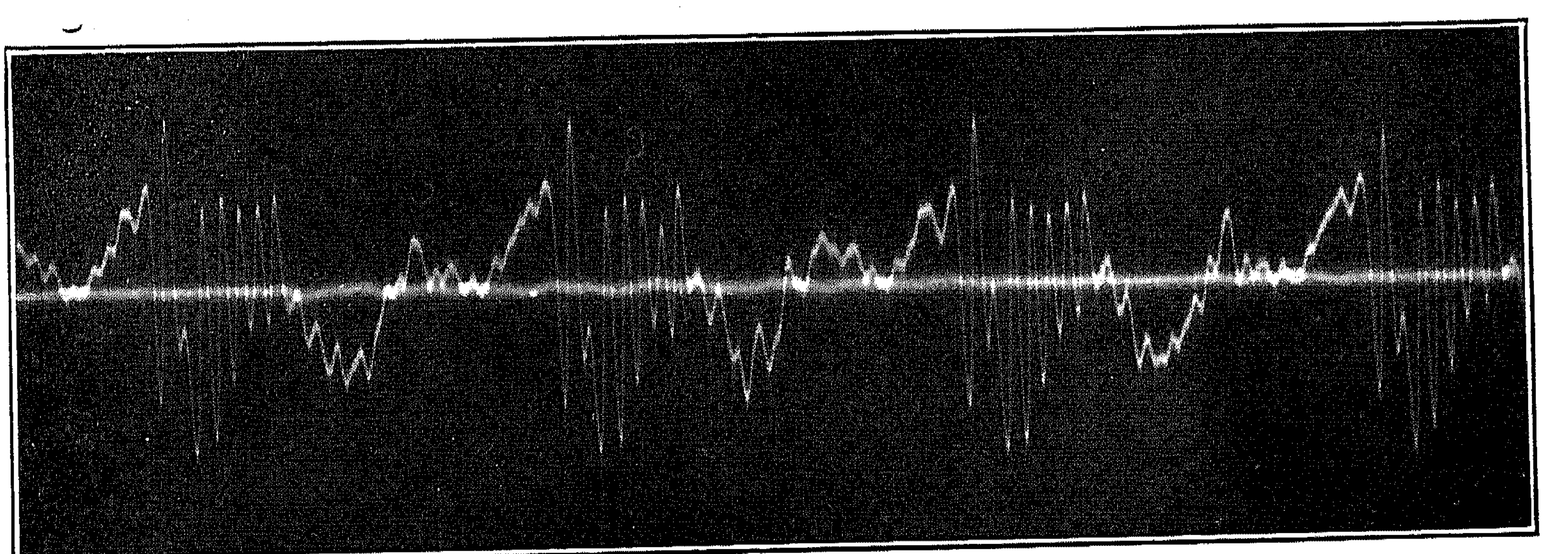


FIG. 4 [TAYLOR]

cycles (which is the *pitch* of the voice) may be lowered or raised to the pitch I may desire to speak or sing without materially changing the 720 cycles. Three typical oscillograph records with the voice differently pitched, are shown in Fig. 3 and 3a. If curves of this character are analyzed, as is frequently done by Fourier's series, the fundamental is practically absent and a long list of harmonics each with a particular phase relation is needed to approximate the record. Some experimenters have maintained that given a tuning fork for each of the harmonics shown by the analysis, that the vowel sound could be produced synthetically, but this I doubt unless special means were provided to secure also the definite phase relations indicated by the analysis. Furthermore, it appears probable that the 720-cycle vibrations are not always regularly continued from one intensity cycle to the next, so that the harmonic series of tuning forks could not be made to match the voice vibrations in this respect. The situation is analogous to the damped wave trains of spark telegraphy. The spark frequency may be 120 cycles per second (there being, however, no radiation of wave-length corresponding to this frequency), though the tone which is heard is of the spark frequency and the actual vibration frequency is not sensed. Other vowel sounds may be similarly though not so simply described. If the essence of the vowels is an intensity cycle recurring with a rapidity which we distinguish as the pitch of the note, it is evident that we have something here quite distinct from the harmonic theory or the absolute pitch theory.

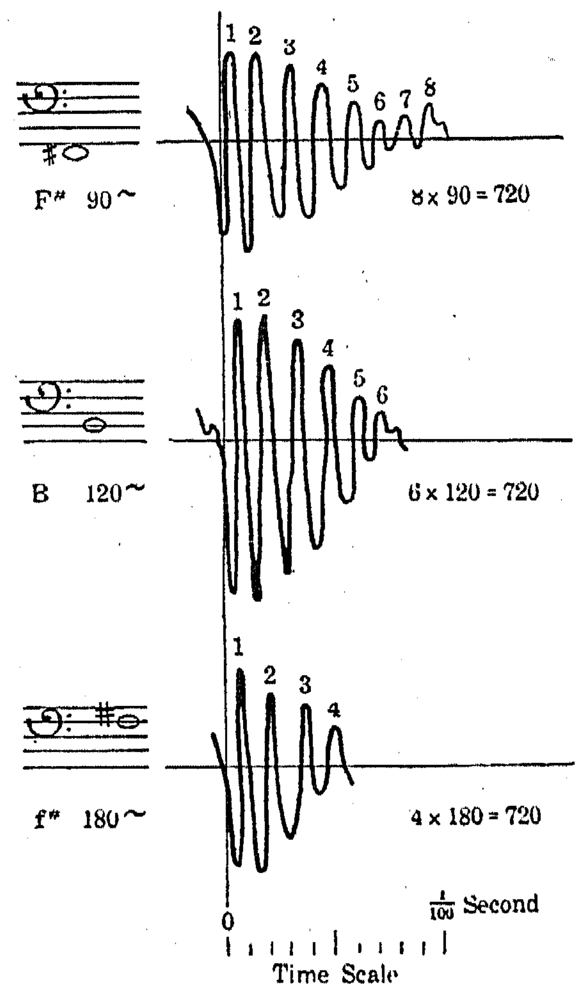


Fig. 3a—Comparison of Oscillograms of Vowel "A" at Three Different Pitches

I have regarded the "curve of intensity" as determined principally by the form of opening, and character of vibration at the vocal cords. Thus, in the case of the vowel *A* discussed, the opening is rather sudden and the closing gradual, which regulates the admission of air in such a manner as to cause the production of 720-cycle vibrations from throat, mouth or nasal cavities. In other words, the vocal cords are not the seat of the sound vibration but a throttle valve in a supply pipe. In this explanation, I differ from what Mr. Flowers offers where he speaks of the mouth and the behavior of the mouth muscles as producing his patterns in the case of a sustained vowel.

The best evidence which I have for my opinion rests on stroboscopic observations of my own vocal cords, pitching the voice to the period of intermittent illumination of the rotating strobo-

scope. Referring still to the vowel A, the vocal cords were seen to be vibrating at 120 cycles per second (the intensity frequency) instead of 720 cycles (the principal sound vibration frequency as disclosed by the oscillograph.)

The stability of the 720 cycles for my own voice on the vowel A might appear to lend support to the fixed pitch theory. However, at the same time and with the same apparatus with which these records were made, my wife's voice showed a characteristic 960 cycles for the same vowel. For this vowel Helmholtz assigns 1096 cycles. Also my records for the vowel *i* (as in pique, and more familiar in English as *ee*) Fig. 4, show pronounced vibrations at around 2000 cycles which is in fair agreement with the 2500 figure given by Mr. Flowers in his *ee* sounds. For this vowel Helmholtz gives 2322.

I do not see the justification for taking these records with whispered rather than with voiced sounds. While no special training seems to be required for whispering or for understanding the whispered word, perhaps too much is taken for granted in relying on such records as basis of design and construction of machines to operate with *voiced* words. The essential distinguishing physical features may not be the same. I made some observations with whispers but felt that the hissing and breath sounds were confusing and tending to conceal the essential data sought.

I see no reason why study and training may not enable one to read the spoken word from some form of photographic or other sound record, but such a record would have to be many times longer than a line of type corresponding to the same words. I have given some consideration to a visual device whereby a trained deaf person might see the word spoken by another, but fear such a reading is almost impossible of attainment, judged by the speed at which a printed page can be read. Similar time and space objections would appear to hold in a voice-operated machine of the type outlined by Mr. Flowers. If the paper cylinder rotates fast enough to make the consonants easily distinguished, the vowels and pauses will use up yards and yards for even moderate length sentences. Is there any marked saving in space, and why should his special form of record produced by resonant circuits, controlling mirrors and selenium cell, be as accurate or any more easily deciphered than a continuous record such as would be given by combination of telephone and oscillograph?

The problem is a fascinating one and Mr. Flowers is not the first to design devices nor to attempt the construction of apparatus. The earliest definite attempt in this line which has come to my notice, is that of Barlow about 1874. He called his device the "logograph" and arranged an India rubber diaphragm about $2\frac{1}{4}$ inches in diameter to draw a line on a moving strip of paper. Deflections of about $\frac{1}{2}$ inch were obtained as the apparatus was arranged. See *Journal of the Society of Telegraph Engineers* (England, vol. VII, 1878, page 65).

John B. Flowers: Many interesting and valuable suggestions have been added to my paper on "The True Nature of Speech," and I have considered them all with deep interest. To answer them fully and with the hope that the reply would be conclusive and definite, is not possible until after the completion of the voice-operated phonographic alphabet writing machine. With a set of pattern pictures of the speech sounds as produced by this machine, it will be possible to definitely establish such important points as were brought up by Dr. Williams and Mr. Chubb, that certain of the vowel sounds may be pattern pictures or low-frequency beats produced by combining resonance tones of nearly the same pitch. I note with satisfaction that the main idea of the paper is pretty generally accepted, viz., that the speech sounds are each represented by a special pattern or form picture as shown in the table called the phonographic alphabet. How absolutely necessary it is that a form picture of the sound wave should be the means of distinguishing the different alphabet sounds one from another, is well put by Mr. Taylor, when he explains that, if a definite fixed pitch stood for an alphabet sound we should often hear the speech sounds when listening to an orchestra.

In reply to Mr. Taylor's interesting statement regarding the formation of the vowel sounds as being determined by the form of opening, and character of vibration of the vocal chords, I have personally learned by stroboscopic observation of the vocal chords of several persons by the assistance of a throat specialist, that the vocal chords are absolutely quiet during the *whispered* vowel A (as in far), the same vowel tried by Mr. Taylor. This then proves that the formation of the vowel A sound is not determined by the vocal chords but is due to either the natural coming together of certain resonance tones of the throat, mouth, and nasal cavities, thus forming low-frequency patterns or beats, or is an intensity variation controlled by the muscles of the lungs, throat and mouth, utilizing a muscle tremor. In this connection, it is important to note that the muscles of the human diaphragm and lungs are mainly controlled by the phrenic nerve and are operated by nerve impulses varying between 30 and 100 cycles per second. The inference can be drawn that when the air is expelled from the lungs by the diaphragm muscle in forming a vowel sound, it comes out in intensity pulses of a definite shape and period corresponding to that of the nerve impulse. I am quite sure that this is the explanation for the intensity variation of such a simple sine wave curve as that of the alphabet sound O, curve No. 17.

In answer to the query why the special record obtained by the voice-operated machine of my design would be more condensed and more easily deciphered than a combination of telephone and oscillograph, I submit the following illustration. Assume that the word *boat* is spoken and it is to be recorded in the phonographic alphabet. This is the phonetic word bōt. The

time required for utterance is (for ordinary speech) approximately b in 1/50 second, o in 1/4 second, and t in 1/25th second. Let the cylinder of paper for the record rotate at a speed of 3 inches per second; then the pattern b is 1/16th of an inch long, o is 12/16ths of an inch long, and t is 2/16ths of an inch long. The resulting record occupying a space 15/16th inches long in contrast to that of the typed distance of 9/32 inches. Therefore, the record of the voice-operated machine will be 3 1/3 times the length of the corresponding letters if typed. It is evident that the combination of telephone and oscillograph only writes down the compound speech curve *without analyzing* it into its elements and the resulting record has been found so complex owing to the compounding of different tones and their variations in intensity, that it is practically impossible to decipher it. But the voice-operated machine would have the power of writing down in the form of the phonographic alphabet the variations in intensity of any of the speech-tones which operate the resonating elements of the machine *after analyzing* the compound speech curve into the tones of which it is composed.

Presented at a section meeting of the American Institute of Electrical Engineers, Denver, Colo., February 19, 1916.

THE FUTURE OF WATER POWER IN THE UNITED STATES

BY CHARLES W. COMSTOCK

ABSTRACT OF PAPER

This paper gives a careful compilation of figures showing the total fixed installed primary power in the United States and similar figures for total installed water power, at the same time calling attention to the unreliability of statistics in general. With these figures, those compiled by the Commissioner of Corporations are summarized and compared.

The geographic distribution of installed water power is considered and many interesting facts revealed when these figures are examined from the viewpoint of population distribution. A study of the development of water power between 1889 and 1909 shows some interesting differences as compared with distribution of manufacturing power and total developed water power.

The author next takes up the question of the possibilities of water power development and points out the fallacy of power development waiting upon demand instead of creating it. The immense field for hydroelectric power which a development of the electro-chemical and electro-metallurgical industries would create with the success of such industries abroad is cited and an appeal made for a Federal policy of encouraging business enterprise instead of obstructing it.

IN PRESENTING this paper before an organization of electrical engineers, I wish to say by way of preface that it is not electrical, nor yet engineering. It is, if anything, economic; in some degree comparative, and slightly statistical. Having in mind Disraeli's classification of untruths as "lies, damned lies, and statistics," you may know what to expect.

In order to get ourselves properly oriented, as the surveyors say, it is well to take a bird's-eye view of the entire power field. The total fixed installed primary power in the United States, as given by the Census Bureau, is as follows:

The unit is the horse power.

Commercial and municipal central electric stations, 1912	7,528,648
Street and electric railways, 1912	3,665,051
Steam road electrification, 1912	193,956
Total electric installations	11,387,655
Manufacturing, 1909	16,802,706
Mines and quarries, 1909	4,402,554
Total fixed installed primary power	32,592,915

The Census Bureau has a disconcerting practise of collecting some of its data as of the years ending with two and seven, while other information is gathered for the years ending with four and nine. Our figures are, therefore, out of phase, the electric power data leading by 216 degrees, and we are not strictly within our rights in making these numerical additions, but the results will serve our purposes for general comparisons.

The figures here given for manufacturing and for mines and quarries are exclusive of nearly two million horse power classed as rented power, which is included under the central electric stations. No account is taken of the power installed in isolated plants, such as hotels, large mercantile establishments, office buildings and the like. The aggregate of these must be very large, but they have not been included in census returns, and no list of them is believed to exist.

In addition to the fixed power, consideration must be given to the power generated by steam locomotives. There are in the United States about 65,000 locomotives in service. It would be absolutely meaningless to add their rated horse power, even if it were obtainable. Doubtless it exceeds the total fixed power of the country. We can, however, by an indirect method, approximate its equivalent in fixed power. In the year ending June 30, 1914, the railroads of the country expended, in round numbers, $242,000,000 for locomotive fuel. .A small portion of this fuel was oil, but far the larger part was soft coal. If the average price of this coal be assumed at $2.00 per ton, the locomotives burned 121,000,000 tons (1 long ton = 1.01 metric ton) of coal during the year. Allowing 26 tons per h.p-year (about six pounds (2.7 kg.) per h.p-hr.), the equivalent continuous output is 4,692,000 h.p., or, with a 60 per cent load factor, 7,820,000 h.p. If all the railroads in the country were electrified, the necessary installed power for their operation would probably not be far from this latter figure, although, of course, the total coal consumption would not exceed one-third that used under the present system. The fixed installation, in these circumstances, would then be about 120 h.p. per locomotive in service.

The data are not available with which to estimate the power used in navigation, and the inquiry would not be pertinent in this connection, even if we could make the estimate.

We have, then, at the present time in the United States the equivalent of at least forty million horse power in fixed installations, without counting the isolated plants already mentioned,

which must total a very large amount, though we have no basis for an intelligent guess.

How much of this is water power? From the census reports again, we have the following:

Commercial and municipal central electric stations, 1912	2,471,081 h.p.
Street and electric railways, 1912	471,307 "
Steam road electrification, 1912	8,000 "
Total hydroelectric installations	2,950,388 "
Manufacturing, 1909	1,822,888 "
Mines and quarries, 1909	97,460 "
Total installed water power	4,870,736 "

The installed water power is, therefore, 14.94 per cent of the total fixed primary power, or about 12 per cent of all power, including locomotives.

In 1908 the Census Bureau reported to the National Conservation Commission that the developed water power of the country aggregated 5,356,680 h.p., of which 3,396,103 h.p. represented developments not less than 1000 h.p., and 1,960,577 h.p. were smaller developments. These figures, however, were not limited to actual installations, but included many power sites only partially developed, or, to quote exactly, "undeveloped power sites upon which some expenditure had been made."

In a report to the Secretary of Commerce and Labor, dated March 14, 1912, the Commissioner of Corporations stated the developed water power in plants of 1000 h.p. or more, to be 4,016,127 h.p. of which 2,961,549 was classed as commercial and 1,054,578 as manufacturing. These figures are of date June, 1911. The difference of nearly 800,000 h.p. between this estimate of manufacturing power and the census figures of 1909 is probably to be accounted for by small manufacturing plants. To the figures above given, the Commissioner adds 2,000,000 for plants of less than 1000 h.p., making "a grand total, in round numbers, of at least 6,000,000 h.p. as the total water power of the United States, developed and under construction in June, 1911."

A still further addition of 2,638,528 h.p. is made by the Commissioner to cover "the undeveloped power owned or controlled by the concerns reporting developed power." This report of the Commissioner of Corporations may be summarized as follows:

Concerns having 1000 h.p. or more:

Commercial	2,961,549 h.p.
Manufacturing	1,054,578 "
Undeveloped	2,638,528 "
Total	6,654,655 "
Plants of less than 1000 h.p., about	2,000,000 "
Grand Total	8,654,655 "

This appears to be the only basis for the inaccurate statement made by Mr. George Otis Smith, Director United States Geological Survey, in an address delivered before the Second Pan-American Scientific Congress, on December 28, 1915, that "the present installation of water-power plants in the United States is estimated at 8,500,000 h.p." There is an obvious difference between an installed plant and the mere ownership or control of a site. I know of several power sites whose owners are looking anxiously for someone to help them let go of the bear's tail. No doubt it was such misuse of data that prompted Disraeli to place statistics in the next place beyond the damned lie.

Taking into account the fixed power equivalent of steam locomotives, and the certainly large, though unknown, amount of power in isolated plants, it is probably safe to say that the actual water power installations of the United States aggregate not far from 10 per cent of the total installed primary power.

The next point of interest is the geographic distribution of the installed water power. This is shown in the following table:

GEOGRAPHIC DISTRIBUTION OF WATER POWER

	Manufacturing, 1909	Central electric stations, 1912	Electric railways 1912	Total
	%	%	%	%
New England	41.5	7.4	7.4	20.9
Middle Atlantic	25.7	26.8	4.1	24.0
East North Central	11.4	10.0	8.9	10.8
West North Central	4.8	4.1	4.7	4.3
South Atlantic	10.1	14.1	13.6	12.4
East South Central	1.6	1.5	0	1.3
West South Central	0.2	0.2	0	0.2
Mountain	1.2	12.9	4.5	7.4
Pacific	3.5	23.0	56.8	18.7
	100.0	100.0	100.0	100.0

The distribution of the power used in mining and quarrying could not be learned, but the total quantity so consumed is small, and, whatever its distribution, can not sensibly affect these figures.

An examination of this table reveals several interesting facts. One-half the population of the United States is east of the western boundary of Ohio; sixty per cent of the developed water power is east of that meridian. One-half the population is north of the parallel of Denver; seventy-five per cent of the developed water power is north of the same line.

The Atlantic coast states, from Maine to Florida, contain 57 per cent of the developed water power and 41.3 per cent of the population. The states west of the eastern boundaries of New Mexico, Colorado, Wyoming, and Montana contain 26 per cent of the developed water power and 7.5 per cent of the population. The great Mississippi valley region, from Canada to the Gulf of Mexico and from Pennsylvania to Colorado, contains rather less than 17 per cent of the developed water power, with 51.2 per cent of the population. The three Pacific coast states alone contain 18.7 per cent of the developed water power, but only 4.6 per cent of the population.

As we shall see later, all this has a bearing on the alarmist talk about water power monopoly with which we are regaled from time to time by Young-man-afraid-of-his-job or some other member of a Federal bureau, the sole purpose of whose existence is to seek out the unfortunate private citizen who has more than three dollars, and regulate him. With these gentry it is a case of "Johnny, gó out and see what Willie is doing, and tell him to stop it."

The general character of the evolution in the development and use of water power is familiar to all. The first water wheels were installed to drive grist mills, saw mills and other plants whose activities were directly connected with the every-day necessities of the people. Naturally these were in the New England states. As the population increased and its requirements became less primitive, the power sites were further developed and applied to paper manufacture, the textile industries and the like. Even today 41.5 per cent of the water power devoted to manufacturing, as distinguished from that generated in central stations and sold for general commercial purposes, is located in New England, and 67.2 per cent is in New England, New York, New Jersey and Pennsylvania. Nearly all the remainder is in the South Atlantic states and in the states north of the Ohio and east of the Mississippi river.

The water power thus directly applied to manufacturing industries has not increased very rapidly for the past twenty years,

and the growth is likely to be even less important in the future. In 1889 the water power so applied aggregated 1,255,045 h.p.; in 1899—1,454,112 h.p.; in 1909—1,822,888 h.p. The increase was thus 15.9 per cent from 1889 to 1899, 25.4 per cent from 1899 to 1909, and 45.2 per cent from 1889 to 1909. For the same periods the total power used in manufacturing increased from 5,938,635 h.p. in 1889 to 10,097,893 in 1899, or 70 per cent and to 18,675,376 h.p. in 1909, an increase of 85 per cent since 1899, and of 214 per cent since 1889.

The North Atlantic states became important manufacturing centers because of readily accessible and easily developed water powers. Large populations grew up around them and these people in turn constituted a market for the manufactured products. Thus, this region had three of the four requisites for a successful manufacturing country, viz: cheap power, ample labor, and a near-by market. These advantages it still has to a considerable extent, though the first it is rapidly losing.

In the early nineties, hydroelectric development began in earnest. The first Niagara plant (55,000 h.p.) about 1894, was the first important installation of this character. In 1902 the aggregate of the hydroelectric developments of the United States was 438,472 h.p. in central station installations, and 49,153 h.p. in electric railway plants, a total of 487,625 h.p. In 1907 these had increased to 1,349,087 h.p. in central stations, and 91,961 h.p. in electric railway plants, a total of 1,441,048 h.p. or nearly as much as the total installed water power for manufacturing purposes. In 1912 the central station installations had become 2,471,081 h.p. and the electric railway plants 471,307, h.p. a total of 2,942,388 h.p., or 61 per cent more than all the installed manufacturing water power. The increase in hydroelectric installations was 195.5 per cent from 1902 to 1907, 104.2 per cent from 1907 to 1912, and 502 per cent from 1902 to 1912. The proportionate increase in ten years, ending 1912, was more than eleven times the proportionate increase in manufacturing water power in twenty years ending 1909.

A study of the distribution of the development shows some interesting differences as compared with the distribution of manufacturing power and of total developed water power.

New England has only about 8 per cent of the hydroelectric as against more than 40 per cent of the manufacturing power. The North Atlantic states, including New England, have about 30 per cent of the hydroelectric and nearly 70 per cent of the

manufacturing power. The eastern half of the population has only 45 per cent of the hydroelectric with 60 per cent of the total developed water power. The northern half of the population has about 70 per cent of the hydroelectric development.

The Atlantic coast states have 45 per cent of the hydroelectric development, and a little more than 41 per cent of the population. The states between Pennsylvania and Colorado have more than one-half the population, but only 16 per cent of the hydroelectric power. The states from Colorado west have only 7.5 per cent of the population, but 39 per cent of the hydroelectric development.

These apparent anomalies are not difficult to explain. Falling water is a source of power, but we must have fall as well as water. In the Appalachian region there is ample water and moderate fall. In the Mississippi valley the fall is slight and difficult to utilize, except in rare instances. From the Rocky mountains to the Pacific we have plenty of fall, but are frequently short of water. In the immediate vicinity of the Sierra Nevadas there is an abundance of water and many falls which can be utilized at moderate cost.

The Pacific coast states, without coal, and until the development of the southern California oil fields, without fuel of any kind, were quick to grasp their opportunites. What was done in other parts of the country by means of fuel, they hastened to do with the "white coal". Thus, we see that the proportion of the total central station power, which is generated by water, is much greater in the far west than elsewhere. This appears from the following table:

Percentage of Total Central Station Power Generated by Water

New England	21.1
Middle Atlantic	22.2
East North Central	12.2
West North Central	14.3
South Atlantic	40.4
East South Central	10.6
West South Central	2.5
Mountain	64.8
Pacific	58.6

The three Pacific coast states, with 4.6 per cent of the population, have 12.3 per cent of all the central station power in the United States. Of this, nearly 60 per cent or 7.2 per cent of all central station power in the country is hydroelectric.

Now, what are the possibilities? In Water Supply Paper 234, United States Geological Survey, Mr. M. O. Leighton gives some estimates of the potential water power of the United States. Although his paper is entitled "Undeveloped Water Powers," his estimates appear to cover the total water power possibilities, without regard to what portions have already been developed. The paper was published in 1909, and the estimates probably correspond to the data at hand in 1908. The state of Pennsylvania is expressly excluded as information was not available to permit an estimate for that state. Two estimates were made—one, regarded as the absolute minimum, based on the stream discharge "for the lowest two consecutive seven-day periods in each year;" the other, described as "assumed maximum," being the quantity which could be generated during six months in the year. Neither estimate takes any account of storage.

The first is stated as 36,916,250 h.p., and the second as 66,518,500 h.p. Mr. Leighton estimates further that, by the use of all practicable storage sites, the grand total of possible water power development in the United States will be at least 200,000,000 h.p.

These estimates include a minimum of 5,800,000 h.p. and "assumed maximum" of 6,500,000 h.p. for the Niagara river. Under present treaty provisions, not more than 25 per cent of the possible power at Niagara falls can be developed, and of this the United States is entitled to only about 36 per cent.

In 1912 the Commissioner of Corporations revised Mr. Leighton's estimates by making the above correction for the Niagara river, adding 331,000 h.p. for Pennsylvania, and 117,750 h.p. for some other changes, and cutting one-sixth off the whole thing for good measure, arriving finally at the following figures:

	Minimum h.p.	Assumed maximum h.p.
North Atlantic	2,225,000	4,092,000
South Atlantic	2,344,000	4,256.000
North Central	1,733,000	3,558,000
South Central	1,438,000	2,785,000
Western	18,996,000	36,707,000
United States	26,736,000	51,398,000

The Commissioner refused to consider the possibility of greater development by storage. He says: "Any estimate including storage, therefore, must be mainly theoretical." Just what he means is not clear, but his purpose in omitting an important element in power development is obvious.

The above figures are not particularly reliable. They are largely speculative, and are based on very meagre data and grossly inadequate surveys. Moreover, the motive underlying the estimates of the Commissioner of Corporations was not honest. However, we may accept them, tentatively, and see to what conclusions they will lead us.

The following table gives the installed water powers side by side with the minimum potential power as estimated by the Commissioner of Corporations:

	Minimum potential power	Installed power
North Atlantic	2,225,000 h.p.	2,134,000 h.p.
South Atlantic	2,344,000 "	589,000 "
North Central	1,733,000 "	729,000 "
South Central	1,438,000 "	79,000 "
Western	18,996,000 "	1,229,000 "
United States	26,736,000 "	4,760,000 "

It appears from this table that the North Atlantic states have practically exhausted all their available water power, notwithstanding the Niagara developments aggregate only about 270,000 h.p. on the American side, instead of the 518,000 h.p. included in the Commissioner's estimate. The South Atlantic states still have a possible 2,000,000 h.p., and the Central states about 2,000,000 h.p. more, but nearly all the water power possibilities of the future are west of the eastern boundary of Colorado, where there yet remains, even by the minimum estimate, and with no allowance for storage, nearly 18,000,000 h.p. undeveloped. On the basis of the "assumed maximum," the undeveloped possible water power in the western states exceeds 35,000,000 h.p. What this would be if storage possibilities were considered, I do not know.

The three Pacific coast states alone contain about 45 per cent of the potential water power of the country. Their aggregate present development is about 880,000 h.p., leaving possibilities from a minimum of 10,524,000 h.p. to an "assumed maximum" of 22,298,000 h.p. without considering storage.

The "assumed maximum" of potential water power, as estimated by the Commissioner of Corporations, is rather in excess of the present total installed primary power of the United States, including the equivalent of the steam locomotives now in service. This, however, is not to say that if all of this water power were

now installed, the steam plants would cease to operate. Seventy per cent of the possible water power is in the western one-third of the country, with 7 per cent of the people. No matter what the population may become numerically, it is probable that fully one-half will always, as now, live in the great Mississippi basin, for this is the region best adapted to the production of the staples of agriculture and animal husbandry. We are not justified in anticipating such improvement in the art of transmission as will permit the use along the Missouri river of power generated in the Mountain and Pacific states. I do not know the longest transmission line now in operation—someone is always going his predecessors one better—but probably the 238-mile (383.02-km.) line of the Southern Sierras Company is the limit of present practise. Let us suppose that power might be transmitted 500 miles (804.6 km.) with a reasonable loss. A belt 500 miles wide with the summit of the Sierra Nevadas as its western limit would have as its eastern boundary a line passing near Great Falls, Montana, Pocatello, Idaho, across the western edge of Great Salt Lake, crossing about the middle of the southern boundary of Utah, and near Gallup and Silver City, New Mexico. Clearly, no conceivable development in that belt of country would ever call for the use of 10,000,000 to 22,000,000 h.p. How would you like to be the grinding monopoly to own all these power sites and pay taxes on them until such time as you might develop them with a reasonable chance to earn more than their fixed charges and cost of operation? This is the "bogie man" with which our conservation friends are trying to frighten us.

What is to become of all this power if it shall ever be developed? The present fixed installed primary power of the United States, including steam locomotives, is between four-tenths and five-tenths of a horse power per capita. On this basis the minimum potential water power in the Pacific coast states alone would provide for a population of twenty to twenty-five million people west of Great Salt Lake. What would they do? They would be much in the position of the Irish woman and the Chinaman who were ship-wrecked on a desert island—they made money doing each other's washing.

Every important hydroelectric enterprise from the first Niagara installation to the Keokuk plant, has been financed on the basis of an existing market for at least a part of the output. No responsible banking house will listen to a power scheme which can not show a market in sight sufficient to pay fixed charges. The Niagara Falls Power Company was financed on the power con-

sumption in Buffalo and other nearby cities. The Standard Electric and the Bay Counties Power Company, as well as other properties now belonging to the Pacific Gas and Electric Corporation, had their markets in sight around San Francisco bay. Snoqualmie Falls had Seattle, Tacoma and the entire Puget Sound district. The McCall Ferry plant is only seventy miles (120.7 km.) from Philadelphia, and the Mississippi River Power Company had a 60,000 h.p. contract with St. Louis before work was begun at Keokuk.

So it has been with all of them, but it can not continue to be if anything like the enormous quantities of power above mentioned are to be developed within limited areas. We must go back to something like the methods of early New England days. We must choose those industries in which power is the all-important element, locate them within transmission distance of the power sites, and then finance the industries by virtue of their own strength, regarding the power merely as an adjunct. This is in strong contrast with the method of building a power plant and then waiting for someone else to build the factories and buy the power.

Up to this time our power development has always followed a demand instead of seeking to create it. This has not been so generally true elsewhere, nor have we followed the same method in other activities. The Union Pacific railroad would be non-existent today if its promoters had waited for the Indians to petition Washington for improved transportation facilities. The coal range would still be in universal use if the gas range had not been put on the market until the housewives clamored for it.

In the United States most of our power has been used to meet the every-day demands for light, heat, transportation and the operation of such industries as are incidental to city life. Outside of Niagara Falls, we have not developed any electro-chemical or electro-metallurgical industries worthy the name. Abroad it has been quite different. The Norwegian Nitrogen Company, for example, located its plants near the power sites, developed power, not as an end in itself, but as an adjunct only, and built up an enormous industry where before there had been nothing. In 1913 it had in operation 260,000 h.p. used solely for the fixation of atmospheric nitrogen, and had planned the development of 280,000 additional h.p. The furnace and process by which this is done were not invented until 1903.

In 1910 there were in the French Alps operating water-power plants aggregating 475,000 h.p., 80,000 h.p. more under construc-

tion, and 700,000 h.p. projected. Of the power produced at that time, 210,000 h.p. was consumed in electro-metallurgical work and 60,000 h.p. in electro-chemical industries. These made up 57 per cent of the total. Of the remainder, 30,000 h.p. was used in the paper and wood industries, and 165,000 h.p. for commercial power, light and traction. The distribution of this power among the industries is significant.

It has often been said that fixation of atmospheric nitrogen is not practicable in the United States because of the high cost of power. Let us look into this briefly. Nitrate of soda costs \$70.00 per ton (1 long ton = 1.01 metric ton) in New York. This is equivalent to \$95.00 per ton for pure nitric acid. The operations in Norway and elsewhere produce about 500 kg. (1,102.3 lb.) of nitric acid per kw-yr., or 1.82 kw-yr. per ton of acid.

The Mississippi River Power Company supplies power to St. Louis at \$24.00 per kw-yr. at 60 per cent load factor. At this rate the power necessary to produce one ton of nitric acid would cost about \$44.00. The margin between this and a selling price of \$95.00 is sufficient to warrant a very careful inquiry before accepting the statement that "it can not be done."

The greater part of the hydroelectric power in the French Alps devoted to electro-metallurgical work, is used for the manufacture of special alloys, such as ferro-tungsten, ferro-molybdenum, ferro-titanium, etc. The Paul Girod works alone produce more than two million dollars worth of these alloys annually. The western part of the United States is as well supplied with the raw materials for such manufacture as any part of the world.

In northern California the production of pig iron in the electric furnace was inaugurated about six years ago. This experiment has been attended with considerable technical successs though with what commercial results I am not advised. Doubtless that and similar enterprises elsewhere will ultimately succeed. When they shall do so, their demand for power will be very large.

Such and many other industrial undertakings will grow up in the western part of the United States when a Federal policy of encouraging business enterprise and initiative shall take the place of the present obstructive tactics whose justification is attempted on the ground that someone may corner 22,000,000 h.p. in water falls, and that the world would then freeze to death in about five thousand years. When that freezing takes place, certain Federal bureaus and officials will not be suffering from the cold.

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IRON LOSSES IN DIRECT-CURRENT MACHINES

BY B. G. LAMME

ABSTRACT OF PAPER

The term *iron loss*, as used in connection with rotating machinery, is shown to cover a large number of losses, some of which actually do not lie in the iron itself. The term *core loss* should be used except when the losses are actually located in the iron itself. It is shown that no great accuracy is practicable in the calculation of the actual iron losses, except in special instances, due to the fact that the ordinary treatment of materials in manufacture is such that large discrepancies are almost sure to occur, in certain types of apparatus. A brief explanation of several causes of variation in losses is given.

In the treatment of core losses in direct-current machines, the four principal sources of losses are considered, namely—armature ring loss, armature tooth loss, eddy currents in buried conductors, and pole face losses. Under eddy current losses is given an explanation of certain losses not usually taken into account, and a crude method of calculation is given, with some tabulated results.

Under pole face losses an empirical formula is given, also some tabulated results.

The effect of load on losses is discussed, but no calculated results are given. Some of the effects of flux distortion on the losses are shown.

A principal object of the paper is to show the impracticability of calculating all the core losses with any great accuracy at no-load, and the still greater difficulty in predetermining them with load.

IRON LOSS is a general term to cover a number of losses,, of various kinds, which, by the nature of the tests, are included in one set of measurements and which, in reality should be known as core loss. The term has been used so promiscuously, without indicating what it really includes, that many have come to believe that it means the true iron loss and nothing else. In fact, however, the true iron loss, in many cases, may be only a moderate percentage of the core loss. Usually no distinction has been made between losses simply located in the iron, and those due to the magnetic conditions in the material itself. The readily practicable methods of measuring the core losses show only their sum and there is no true indication of the relative values of the various com-

ponents. To separate the total core loss into its various components, except by complicated and expensive laboratory methods, appears to be almost impossible. However, it is possible to indicate the various components and their probable causes, and in some cases they can be segregated very crudely by calculation.

In most rotating machinery the calculation of the individual elements, which make up the total core loss, is necessarily only approximate, in commercial apparatus. This is due partly to the fact that there are many possibilities of variation in loss on account of conditions of manufacture and materials, as will be described later. This is evidenced by the fact that two machines, built at different times from the same drawings and the same tested grade of materials, will ofttimes show materially different core losses. If two such machines vary twenty per cent from each other in core loss, it is obviously impracticable to expect any refinement in calculation closer than twenty per cent. Even if we always could come within twenty per cent by direct calculation and could place any great reliance upon the results, it would be a great step ahead, in certain types of apparatus. In the discussion of the various losses and their causes, given throughout the following paper, it will be shown why it is impracticable to calculate, with any exactness, certain of these losses.

In separating the total core loss into its components, two principal classifications of losses may be made. One of these is eddy current loss, either in the iron laminations themselves or in other conducting parts wherein e.m.fs. are generated during rotation. Such e.m.fs. will set up local currents where closed paths are possible, and if such paths are in the laminations themselves, instead of in neighboring solid parts, it is simply incidental. Eddy current loss in the laminations is, therefore, not a special kind of loss, and it should rightly be classed with other eddy losses in the machine.

The second class of losses includes those due to changes in the magnetic conditions in the iron itself; these are known as hysteresis losses. These latter are dependent upon the material itself and not its structure. Lamination is primarily for increasing the resistance in the eddy current paths and not for the purpose of affecting the hysteresis. In fact, lamination may increase the hysteretic losses, for a given volume of material.

The principal object of this paper is to show causes for some of the principal losses. These are usually related to two sets of frequencies, namely, the normal frequency (revolutions per second times number of pairs of poles), and some very high frequency, dependent upon the number of slots, commutator bars, etc. The hysteretic losses are undoubtedly affected by these higher frequencies but apparently not to the same extent as the eddy losses. These high-frequency losses are liable to be present in most classes of rotating machines, while in some instances they may overshadow all other losses. Certain of them are characteristic of certain types of machines only, while others are liable to be present in any type of rotating machine.

In most classes of rotating machines, only the no-load core losses can be measured with any accuracy by ordinarily convenient methods of measurement. However, if the various components of the no-load loss can be approximately determined, then it is possible to indicate in what way these same components will be affected by load. A quantitative determination of the component losses with load is, however, very difficult to determine except in a very few classes of machines.

In direct-current machines the principal no-load armature core losses are the hysteresis loss in the iron, eddy losses in the iron and copper, and eddy losses in other adjacent conducting parts, which may be seats of e.m.fs. The relative values of these losses are dependent upon many conditions. In a thoroughly well designed machine the eddy losses in the copper and any other parts than the iron should be relatively small compared with the iron loss proper. Again, the proportion of hysteresis to eddy loss in the iron itself depends upon many conditions, such as the various frequencies in the machine, the grade of material, the degree of lamination, the perfection of the insulation of the laminae from each other, the distortion of the material in handling and building, the conditions of punching, treatment during assembly, grinding, filing, etc. Here, at once, so many variables appear that one cannot reasonably expect any great accuracy in any predetermination of eddy loss in the iron itself. Hysteresis loss is also affected by some of these conditions.

It is a fact well known to designers that the iron loss tables used by transformer engineers do not directly apply to rotating machinery, but that an increase, in some cases, of one hundred per cent or more is necessary, depending upon the

type of machine. This increase is due largely to additional causes of loss which do not occur to any appreciable extent in transformers. Some of these additional losses are as follows:

(a) Handling of iron. Experience shows that well annealed armature iron will have its losses very materially increased by springing or bending. If a lamination is given a decided bend, beyond the elastic limit, and then is straightened out, the loss at the part which has been bent may be increased as much as 100 per cent. This fact must be taken into account in machinery where armatures with many light teeth are used. Here it is almost impossible to prevent some abuse of the iron, especially in the teeth, which are the parts usually worked the hardest. Furthermore, tests have shown that if iron is bent, even at a small angle, and not beyond the elastic limit, the loss is materially higher with the iron in this strained condition, although the loss may return to normal when the iron is allowed to spring back to normal position. And if the iron is annealed in a curved or warped position, then when straightened out in building the strain is present, with increased loss. In building up armature cores, undoubtedly part of the iron is put under stress, especially in the teeth. Any dent in the iron, produced by hammering or otherwise, also tends to increase the loss.

(b) A second source of increased loss in the iron is due to the operation of punching. In shearing the iron a small amount adjacent to the sheared part is affected much in the same way as when iron is bent beyond the elastic limit. In transformer plates this strip next to the sheared edge represents but a very small percentage of the total volume of each plate or lamination. However, in armatures with many comparatively long narrow teeth, this sheared part may represent a relatively large percentage of the whole plate and, moreover, this is a part which often has the largest losses. But this may not have as great effect on the losses as another result of the shearing, namely, the sharp burrs which are left on the iron. These may be very small or almost negligible in appearance and yet represent quite a large percentage of the thickness of the plate. For example, a burr of two mils height, or 1/500 in., seems to be very small indeed, and yet it is about 12 per cent of the thickness of a 17-mil lamination. Dies must be maintained in very good condition to keep the burr below two mils. The effect of this burr is to bring increased thickness and pressure

at the edge of the sheets, particularly at the teeth. If the laminations are all turned one direction in building and the edges match perfectly the sheets might fit together so accurately that the burr would cause no extra thickness. But it is impossible to obtain such accuracy in practise and, therefore, the burrs of one sheet "ride" upon the surface of the next sheet, thus increasing the total thickness of the built-up iron. In practise, however, the iron is pressed down to approximately uniform height throughout. This means that the burrs carry considerable of the pressure at the armature teeth and there is more or less of a tendency to cut through the insulating film on the plates, thus increasing the eddy current losses. This is obviously a variable condition depending upon the accuracy of building, upon the condition of the dies, etc., and no method of calculation can take this loss into account with any accuracy. In small machines with low voltage per unit length of core, this loss usually is not of great importance. However, in high-speed large-capacity machines, it becomes increasingly important and in some cases special means are used for removing the burr before insulating the individual armature plates.

(c) Another source of iron loss, and one which also is beyond the scope of calculation, is found in the filing of armature slots and cores. In ideal armatures with perfect punchings and assembly, there should be no occasion for filing. However, the practise, in many cases where the armature iron does not build up with perfectly smooth surfaces in the slots, is for a limited amount of filing to be done. Usually this takes off only isolated high spots, so that the adjacent laminations are not bridged over to any great extent by the burrs due to filing. The tendency of most workmen is to file down to a nicely polished surface, whereas a coarse filing gives better results as it tends to break the laminations away from each other. Filing is most harmful in machines having a relatively high voltage per unit length of core. A milling cutter for cleaning out slots is usually worse than a file, as it produces greater burring of the edges. However, if the milling is followed by filing with a very coarse file the results may be just as satisfactory as with filing alone. Obviously, no method of calculation can show accurately the losses due to such burring.

(d) The iron losses are affected to a certain extent by pressure, that is, by the tightness with which the core is clamped.

The loss due to this is probably closely related to some of the preceding losses, such as bending and springing of plates, effect of burrs, etc. In small machines the effect of pressure apparently is of little moment, but in large very long cores it may become very appreciable. It is particularly noticeable in large turbo-generator armatures where the cores are very wide. In such machines, in attempting to draw the core down to a sufficiently solid condition as a whole, the parts next to the end plates are liable to receive abnormal pressure, with consequent increase of loss in those parts. For this reason, it is the practise in some cases to add an extra separation of paper at frequent intervals near each end of the core. Experience shows that this equalizes the losses and temperatures very materially. That this is due to undue pressure and not to stray field or other conditions, is indicated by the fact that when high temperatures are found in the iron, at each end of the core, very often the condition can be relieved by simply lessening the pressure to a comparatively small extent. The writer has known cases where the temperature in the end sections of the iron has been reduced 30 to 50 per cent by "easing off" the end plates. The total loss in the core may not be reduced very much, for the reduction in pressure usually affects only the end sections to any great extent. Presumably this loss is due to increased contact between the adjacent plates, possibly from the burr, but not entirely so, for similar results have been found in some cases where the burr had been fairly well removed before enameling the plates. The character of the enamel coating used for insulating purposes also has something to do with this.

In connection with pressure, the effect of heating of the core may be considered. Cases have been noted where the effect of high temperature of the core has been to increase the pressure between the laminations, due to expansion. This in turn increased the loss and thus still further increased the temperature. This effect has not been uncommon, to a minor extent, but a few cases have occurred where the combined pressure and temperature cumulatively have resulted in excessive core temperatures. In one case which the writer has in mind, a certain large machine operated for about two years without any noticeably high temperature in the core. Then, in a comparatively brief time, it showed evidence of increasing temperature until finally an entirely prohibitive tempera-

ture showed at one place. Examination showed that the core was very tight and all evidence indicated that increased temperature was causing increased pressure and thus further increasing the loss. In this machine, fortunately, the construction of the armature core and winding was such that the end plates could be released very easily about $\frac{1}{4}$ in. on each end. This was tried as an experiment and the temperatures all returned to the former normal of about 30 deg. cent. rise. As an interesting side issue, it may be mentioned that on this machine the armature teeth at each end of the core had been breaking off, although stout brass supporting fingers had been used. Apparently under the increased pressure, due to heating, the fingers would be bent away from the core, thus releasing the tooth laminations. Repeated tightening of the brass fingers did not relieve this condition. However, when the end plates were released $\frac{1}{4}$ in. at each end of the core, the brass fingers were then sprung in against the teeth and afterwards remained in position so that no breakage of tooth laminations was ever reported afterwards.

Obviously, with losses dependent upon pressure, no extreme accuracy in calculation of such losses is possible. However, in moderately small size machines, and especially in those of very moderate frequency and of very low voltage per unit length of core, the effect of pressure is not serious, within a moderate range of practicable pressures.

(e) Another source of iron loss, but which is not in the armature core, is that of the pole face, due to the tufting or bunching of the flux between the field pole and the armature teeth, where slotted armatures are used. Obviously, with all other conditions the same, this pole face loss will depend upon a number of variables in the lamination of the material itself. The effect of burrs from punching, the burring over of the surface due to turning, the effect of pressure, etc., all appear in the pole face loss. Therefore, it is evident that great accuracy in the calculation of such loss is impossible, in commercial apparatus. There are other conditions that affect this pole face loss which will be considered later under this subject.

Armature Ring Loss. The true iron loss in the armature ring is dependent upon the total flux per pole, distribution of flux, rate of change of flux, etc. The problem is much complicated by the fact that the flux distribution in the ring usually

is not uniform, that is, certain parts of the core have higher maximum densities than other parts. However, in ordinary practise the core densities used are relatively low, so that the losses can be approximated by averaging the inductions in certain parts. However, the rate of change of flux in the ring is dependent, to a certain extent, upon the flux distribution in the air gap and armature teeth, and this introduces some error, always in the direction of increased loss.

The distribution of flux in the armature ring is also dependent upon the effective length of the various flux paths. These latter will naturally depend upon various conditions, such as the number of poles, diameter of armature, flux distribution in the air gap and teeth, etc. Therefore, any method which does not take this distribution into account is necessarily only approximate. However, in practise there are so many other variables, as already described, in connection with manufacturing conditions, such as burring, filing, etc., that empirical rules have been developed, based upon numerous tests, which approximate the armature core loss in a standard type of machine about as accurately as any attempt toward exact calculation.

Armature Tooth Losses at No-Load. Apparently the flux densities in the armature teeth can be calculated with more accuracy than in the various parts of the core, for in the teeth the fluxes are limited to fairly definite paths. Therefore, exclusive of the losses due to manufacturing conditions, as already described, the tooth losses can be fairly accurately calculated, probably with much greater accuracy than many other losses, as will be described. The tooth losses may be considered further as follows:

The flux density in each individual armature tooth passes through a cycle, indicated by the shape of the field form. With the field form of the shape illustrated in Fig. 1, the tooth density will be a maximum at A, and this density will remain practically constant as the tooth moves toward C until the point B is reached. It will then decrease as the ordinate of the field form curve decreases and will reach zero value at C. The cycle of flux change is not sinusoidal, and therefore, the actual tooth iron loss should not agree with that represented by the usual iron loss curves based upon sinusoidal changes in induction. The difference, however, may be relatively small in the ordinary types of machines. The error may be

taken care of by some suitable correcting factor, which, of course, will be only approximate for the average case.

The density in the armature teeth is involved in the iron loss. This density is not uniform over the entire depth of the tooth, with the usual parallel-side slots, for the section of the tooth tapers off. This difference of section, in small diameter machines, may be very considerable. However, a higher density at the base of the tooth, tending to give higher iron loss, is compensated for, to some extent, by the reduced volume of material. In consequence, the mean section at some point from one-half to two-thirds the way down the tooth may be taken and the mean density and volume of material, based upon this section, may be used for approximating the iron loss. The accuracy of this method will be dependent, to some extent, upon the actual density used. For instance, if both the minimum and maximum densities in the tooth are relatively low, then the loss calculated for the mid-point density, at the mid-point section, will be closer to the true loss than if the maximum density is excessively high.

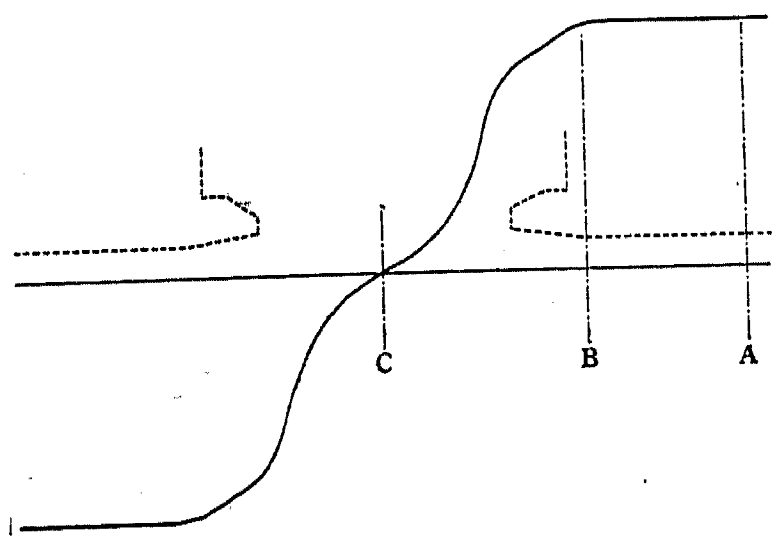

FIG. 1

Armature Copper Eddy Current Loss at No-Load. There may be a number of eddy current losses in the copper, some of which are of a minor nature. However, there may be two relatively large losses, depending upon the design of the machine. One of these is due to the flux from the field poles entering the armature slots and cutting the conductors. This is, to a certain extent, a function of the saturation of the tops of the armature teeth. It is also dependent upon the width of the slot opening compared with the iron-to-iron clearance. At first thought, one would say that the larger the air gap the more would the lines from the pole pass into the tooth top. However, the opposite is the case, for the larger the gap, the nearer do the lengths of paths into the slot approach to the iron-to-iron clearance, in percentage.

In moderate size machines with relatively small air gaps and moderate slot widths, the eddy current loss from fringing into the top of the slot is comparatively small, and, as a rule,

no special precautions need be taken to minimize it. This particular loss is usually greatest in high-voltage, large-capacity turbo-alternators, where relatively wide slots, up to 1.5 in. or more, may be used, and where the air gaps are very large. In such cases lamination of the top conductors to avoid eddies from this cause may be desirable.

The second source of eddy current loss in the copper, which is liable to be larger than all others combined, is due to the peculiarities of flux distribution in the armature teeth. Let Fig. 2 represent the magnetic conditions in a given machine. It is evident from this figure that under the central flat part of the field form, the armature teeth are worked at a uniform induction, assuming that there is no field distortion. However, at the edges of the pole the tooth density decreases slightly. If the saturation of the teeth under the flat part of the field form is very high (materially above 120,000 lines per sq. in.), the ampere-turns required to magnetize the teeth may be very considerable. However, at the edge of the pole a comparatively small decrease in the flux density in the teeth (15 to 20 per cent) will mean a relatively enormous decrease in the ampere-turns for the teeth. For instance, the tooth c in Fig. 2, under the central flat part of the field form, may require 2000 ampere-turns, while the next tooth b, under the pole edge, which is worked at possibly 20 per cent lower density, may require only 10 to 20 per cent as many ampere-turns. Assuming such conditions, then the magnetic potential at the top of tooth c will be higher than that at the top of b by 1600 to 1800 ampere-turns. Therefore, under this condition there will be a very considerable flux across the slot between c and b. A little earlier or a little later in the rotation this flux across this slot will not exist to any extent, for the ampere-turns for b and c will then both be comparatively low or very high, while the difference between them will be small. In consequence, near each pole edge, there is a very rapid rise and fall of flux across the armature slots. This is illustrated in Fig. 2.

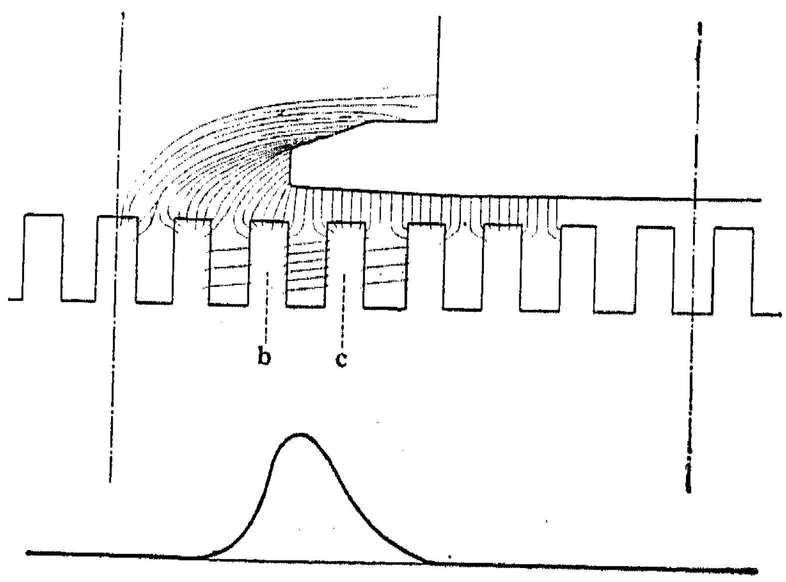

FIG. 2

Obviously, the armature conductors lying in the path of

this flux will be the seat of e.m.fs. which will tend to set up local currents, the value of which will be some function of the e.m.f. producing the current, of the dimensions of the conductor, etc. If the flux across the slot is large, this e.m.f. may also be considerable, for the rate of this flux change will be high compared with the normal frequency of the machine. As the e.m.f. generated is a function of the maximum difference between the ampere-turns required for two adjacent teeth and as the loss in any given case will vary as the square of the e.m.f., obviously the loss in one slot will vary as the square of the maximum difference between the ampere-turns of two

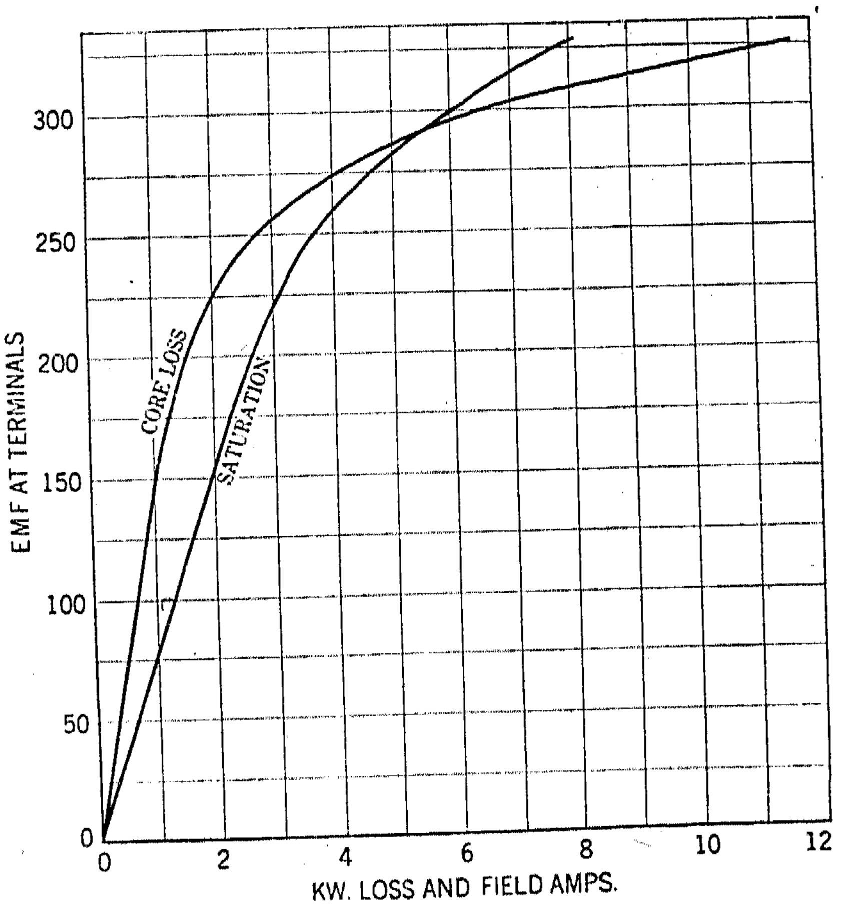

FIG. 3

adjacent teeth. At very high saturation, the maximum difference between the ampere-turns required for two adjacent teeth may be relatively high and the loss may be correspondingly great. Due to the shape of the permeability curve of steel at very high saturation, the difference between the ampere-turns of two adjacent teeth may increase faster than the square of the terminal e.m.f. Therefore, the eddy current loss due to this cause may increase faster than the *fourth power of the total induction per pole*. Evidently, therefore, it is desirable to keep these eddy current losses at a low value at no-load, for the high tooth ampere-turns under the distorted field conditions of full load will tend to increase the percentage of these losses very greatly. Fig. 3 shows a characteristic core loss

curve for a generator in which the copper loss, due to the above cause, is very large at the higher e.m.fs.

Several years ago, the writer spent considerable time in attempting to determine the value of this eddy current loss at no-load. Neither sufficient nor entirely satisfactory data were available. From the data at hand, the following empirical formula was derived, which appeared to accord fairly well with the facts in a number of cases which were worked out. This formula applies, however, only to windings with two conductors in depth per slot. This formula for the loss in conductors is

$$\text{Watts loss} = \frac{180\ V_c\ R_s\ p\ (1000 + a)^2}{10^8}$$

a = Maximum ampere-turns for one tooth.
V_c = Total volume of copper, in cubic inches, in one slot.
R_s = Revolutions per second.
p = Number of poles.

The values for the watts eddy current loss in the copper were approximated by taking the iron loss curves at the lower e.m.f. values (where the above eddy current loss would be very low), and then projecting them for the higher values according to the laws which the iron loss alone should follow. The difference between this corrected iron loss and the actual test curve was assumed to consist largely of eddy current loss. As this difference usually increased very rapidly at higher inductions, the above assumption was in line with the preceding statements that this eddy current loss may increase much more rapidly than the square of the flux. In this determination obviously the pole face loss would have to be taken into account. This was taken care of as far as possible, by tests with relatively large air gaps, the pole face loss thus being very small.

It may be noted that in the above empirical formula, the ampere-turns for one tooth under the maximum field has been used, instead of the maximum difference between the ampere-turns of two adjacent teeth. However, the tests indicated in general that the maximum difference was approximately proportional to the maximum ampere-turns in one tooth and, therefore, it was simpler to use the total turns for one tooth. Also, where the total tooth ampere-turns are tapered off over

several teeth, the difference between the ampere-turns for adjacent teeth is reduced, but more slots and more copper is involved, whereas the empirical formula includes only the copper for one slot. Various attempts were made to include all the different factors, such as ampere-turns across each slot, number of slots, number of conductors involved, counter magnetomotive force of the eddy currents, etc., but none of the resulting formulas gave as consistent results as the above. It must be admitted that this formula is an extremely crude one, but it happened to fit most of the cases that the writer was able to analyze. In deriving this equation, it was found that if the loss was assumed to vary directly as the square of the tooth ampere-turns, then it would be too great at very high tooth saturation. At high tooth densities, the flux across the slots, at the pole edge, is distributed over several successive slots, so that the maximum difference between the ampere-turns of two adjacent teeth bears a lower proportion to the ampere-turns for one tooth. Also, at very high tooth densities there is more or less fringing of flux down through the slot, in parallel with the tooth flux, and this makes the determination of the actual tooth flux difficult. In the formula, therefore, the term $(1000 + a)^2$ is used in place of a^2 to take care of these conditions. This term, however, is obviously wrong, in that it indicates a loss when the tooth saturation is negligible. However, this loss under low saturation usually works out from the formula to be of comparatively small value, so that the error is not of much importance.

A modified formula, which agrees with the above fairly closely at high saturations, but gives no loss at zero saturation, is the following:

$$\text{Watts loss} = \frac{135\ V_c\ R_s\ p\ (4000 + a)a}{10^8}$$

The following table shows the comparison of the copper eddy loss compared with the calculated loss by the first formula above, for a number of machines. It will be noted that the agreement is not particularly close, but possibly as good as could be expected, considering how the test losses were derived. It may be stated that these were all comparatively old types of machines, for in recent years great pains have been taken to eliminate large eddy losses of this character, so

that it was necessary to go to old machines in order to obtain exaggerated cases.

Kilowatt rating	Terminal e.m.f.	Rev. per min.	No. of poles	Calculated ampere-turns in teeth	Eddy loss estimated from test curve; kw.	Eddy loss calculated from formula; kw.
340	600	685	6	1400	2.7	3.4
"	700	"		3000	10.0	9.7
500	600	225	10	2500	7.5	6.15
"	625	"		4000	17.5	12.5
750	250	514	10	1200	1.5	2.76
"	320	"		7200	32.0	39.3
750	550	514	8	1500	4.5	3.3
"	700	"		7000	33.0	36.5
1000	250	514	12	600	2.5	2.2
"	330	"		6000	50.0	41.3
1000	600	514	10	1225	4.5	4.6
"	700	"		2380	10.0	11.3
2000	575	300	14	3000	12.0	7.1
"	675	"		7000	36.0	28.2

Pole Face Losses at No-Load. It has long been known that, with open slot armatures, there are liable to be considerable losses in the field pole faces due to bunching of the magnetic flux from the armature teeth to the pole face, the armature teeth thus acting as small poles of an "inductor" type alternator, of which the pole face, to a small depth, serves the function of the armature core.

While the effect of this "inductor pole" action has long been known, the amount of loss due to it has frequently been underestimated, especially in machines with relatively small air gaps compared with the width of the armature slots.

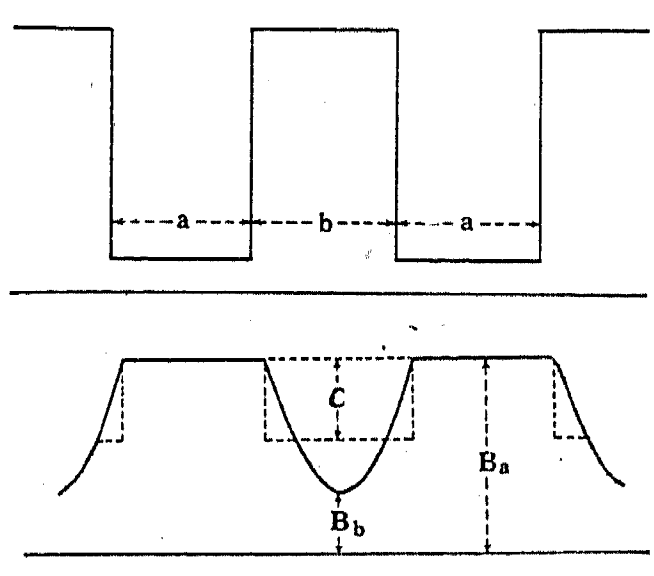

FIG. 4

The following crude description will illustrate the extent of the variations in flux in the air gap due to the open armature slots. In Fig. 4, a represents the width of one armature tooth and b represents the width of one armature slot. Let g represent the single air gap (iron to iron).

In the lower diagram, which represents the flux distribution in the air gap, let B_a represent the flux density in the air gap

under the armature teeth and B_b the minimum flux density corresponding to the center of the slot.

Then, $a \times B_a$ = the total flux under one tooth, for unit width of core, and $b\ (B_a - B_b)\ c$ = the total decrease in flux for the space covered by one slot. c represents the average height of the curve *def* in Fig. 4. If this curve be assumed to be sine shaped, then c would be 0.636. Any other shape which would be likely to be found in practise would not be far from this value. A V-shape, as one extreme, would give $c = 0.5$, while a circular shape, as the other extreme, would give $c = 0.784$. Apparently the value would lie somewhere between these two extremes.

In calculating the effective gap from the above diagram and assumptions, the following equation would be obtained:

$$\text{Increased gap } g' = g \times \frac{(a + b)\ B_a}{(a + b)\ B_a - b\ (B_a - B_b)c}$$

$$\text{Or, } g' = g \times \frac{1}{1 - \dfrac{b\ (B_a - B_b)\ c}{(a + b)\ B_a}} = g \times \frac{1}{1 - \dfrac{(b)\ (B_a - B_b)\ c}{(a + b)\ (B_a)}}$$

The resemblance of this equation to Carter's well-known equation for the increased air gap may be seen at once.

$$\text{In Carter's equation, } g' = g \times \frac{1}{1 - \dfrac{b\ k}{a + b}}$$

Comparing these two formulas, it is evident that k =

$$\frac{(B_a - B_b)\ c}{B_a}.$$

An extremely close approximation to k can be obtained from the empirical formula $k = \dfrac{\frac{b}{g}}{5 + \frac{b}{g}}$. This holds closely

to Carter's curve over almost the entire range. Equating the above two values of k, we obtain the equation

$$\frac{B_a - B_b}{B_a} = \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

Or,

$$\frac{B_b}{B_a} = 1 - \frac{1}{c} \frac{(b)}{(5\,g + b)}$$

This gives the ratio of the flux density at the middle of the slot to the flux density under the tooth.

As an example of what these relative values may be, assume that $a = b$, or the slot width = the tooth width, and that $g = 0.25\ b$, which is extreme for large a-c. or d-c. generators, but not unusual for induction motors. Assuming $c = 0.635$, then $\frac{B_b}{B_a} = 0.3$, or the density under the middle of the slot is only 0.3 of that under the tooth. With these same values, the value of g' becomes 1.2859, or the gap increase is 28.5 per cent, which is not unusual for some machinery. Obviously, a variation in the flux density at the pole face of 70 per cent should tend to give high iron losses in the pole face itself. In fact, some of the inductor type alternators which were in common use a few years ago did not give variations in armature flux materially better than indicated by the above value. Such proportions as the above example would, therefore, be fairly good for an inductor alternator.

The above analysis is given simply to furnish a means for determining the possible variations in the flux density which may be obtained with open slots. This gives a much better conception of the problem than can usually be obtained directly from Carter's formula for the increased length of gap. It also gives a good idea of the possibilities of tooth losses in those cases where the teeth of one element or member of a machine alternately pass under the teeth and slots of the other member.

Considerable work has been done at various times to determine the pole face losses due to open armature slots. The difficulty in determining a workable formula is very considerable, as there are many conditions which may directly or indirectly affect this loss. For example, the thickness of the

laminations, or the material in the pole face, may have an influence. Any general formula for this loss would require different constants for different types of pole faces. One formula for this loss has been given by Professor C. A. Adams and his associates.* The formula is very complex and somewhat difficult to use.

A much simpler formula for laminated pole faces is as follows, for 0.031-in. laminations:

$$\text{Watts loss} = \frac{75\, b\, E^2}{C_f\, W_s^2\, g\, L} \sqrt{\frac{S_c}{R_s\, g}}$$

E = Generator voltage.
b = Width of slot.
g = Single air gap (iron to iron).
W_s = Armature wires in series.
L = Width of pole face.
C_f = Field form constant.
S_c = Total slot space = width of slot $\times$ No. of slots.

It is very difficult to obtain any reliable data on pole face losses alone, for other core losses are liable to be included in any tests. Variation of air gap, with everything else in the construction unchanged, gives a partial measure. However, this changes the field form somewhat and thus modifies the

***Pole Face Losses*, by Comfort A. Adams, A. C. Lanier, C. C. Pope and C. O. Schooley. TRANS. A. I. E. E., Vol. XXVIII, Part II, 1909, page 1151.

$$W_p = S_p \times p \times 0.000462 \left(\frac{B_g}{10^4}\right)^{2.4} \times \left(\frac{v}{10}\right)^{1.55} \times q^{1.5} \times \frac{1}{t_p}$$

W_p = Pole face loss.
S_p = Section of one pole face (average section where the density is B_g).
p = Number of poles.
0.000462 = Constant for $\frac{1}{16}$-in. laminations.
B_g = Density in the gap over the section S_p.
v = Velocity of the armature surface in feet per second.
q = Ratio of width of slot to air gap.
t_p = Tooth pitch in inches.

tooth saturation and the tooth and eddy losses, to a certain extent, thus rendering doubtful the pole face component.

The above formula is neçessarily approximate and applies only to laminated pole faces. The effect of cutting away part of the laminations in order to produce high saturation at the pole face is not included. However, it is possible that this may not influence the loss to any great extent. The greater part of the loss is represented by eddy currents, and cutting away part of the laminations will tend to break up the losses between plates and this may compensate to a considerable extent for the higher densities in the remaining plates. It is hoped that some time in the future more complete data may be obtained, over a sufficiently wide range of conditions, to cover the practical range of ordinary design.

The following table covers a number of machines with adjustable air gaps in which the pole face losses were worked out according to the above formula. Also, the total calculated and the total test losses are given, to indicate the agreement in a general way. The writer is perfectly willing to admit that he believes that the fairly close agreements between some of the calculated and test totals are largely accidental, and they should not be taken as proof of any great accuracy of the methods.

It is obvious from this table that the pole face losses may be comparatively high in some cases, provided the formula is reasonably correct. Evidently, if these losses could be calculated with any great accuracy, the design of the machine might be considerably modified, compared with more recent practise, with advantageous results. The pole face losses will evidently be greatly increased by field distortion when the machine is carrying load. Eddy currents in the copper are also affected by field distortion, and a correct method of calculating both the eddy current and the pole face losses with various loads should lead to considerable modification in the proportions of d-c. machines, in general.

Stray Losses. Under this heading may be included a number of no-load losses which are usually of a minor nature. Among these may be included secondary losses in the armature winding due to unsymmetrical cross-connections or unbalanced voltages in parts of the winding which are connected in parallel. There are various possibilities for losses from this source and, in consequence, it is always advisable to use armature wind-

Kw.	E.m.f.	Rev. per min.	No. of poles	Single air gap; inch	No. of slots	Width of slots; inch	Tooth ampere-turns	Pole face watts	Calculated core losses: Copper watts	Calculated core losses: Core watts	Calculated core losses: Teeth watts	Calculated core losses: Total watts	Total test losses watts
200	250	1150	6	0.156	64	0.406	1635	2060	3660	1200	2500	9420	8500
				0.125			1887	2870	4400	1200	3000	11470	11600
200	250	1200	6	0 25	72	0.391	275	975	895	670	1450	3990	3800
				0.125			395	2200	1075	670	1650	5595	7300
750	250	514	10	0.25	200	0.312	2520	2530	7010	2560	5100	17200	19800
				0.1875			2820	3860	7410	2560	5320	19150	22000
750	550	514	8	0.375	200	0.328	2650	1190	7375	1945	3780	14290	14000
				0.250			2840	2210	7770	1945	4000	15925	15550
1000	600	514	10	0.281	140	0.625	2050	6380	15060	5290	6200	32930	30800
	700			0.281			3750	8680	36500	8320	7800	61300	62500

ings which are as symmetrical as possible. Also, the arrangement of the winding should be such as always to generate balanced e.m.fs. in parallel circuits. This condition is not infrequently overlooked in the design of direct-current machines.

A second cause of undue loss in the armature winding may be occasioned by short-circuiting one or more of the armature coils under an active field. The brushes may be shifted from the magnetic neutral point so that some of the armature conductors are short-circuited under the main field flux; or the neutral point may be so narrow and the brush so wide that some of the armature turns are short-circuiting in an active field, even when the brush is set for the no-load neutral. An armature winding which is considerably "chorded" in a field with a narrow neutral point may have two sides of a coil short-circuited in fields of the same polarity. The e.m.fs. in the two sides of the coil should, therefore, balance each other if the brush is set at the true neutral. However, if the brush short-circuits several coils or turns, obviously only one of them can be at the true neutral and have balanced e.m.fs. set up in its two halves. The other turns may have more or less local current in them, which may be a source of considerable loss.

A third condition may occur when there are considerable pulsations in the reluctance in the air gap under the main poles as the armature teeth move under the poles. This varying reluctance usually gives varying main flux and at a relatively high frequency. The armature coils short-circuited by the brushes will act as secondaries to these pulsating fluxes and in consequence there may be some loss in the short-circuited coils due to this cause. Any solid parts of the yoke or poles may also have losses due to this cause. Usually, however, such losses are small.

A fourth source of loss may rise from stray fluxes from the main fields to the armature, which do not pass through well laminated parts of the armature core. For instance, the ventilating spacers may be so dimensioned and shaped that eddies can be set up in them. Also, the finger plates at each end of the core, the end plates, etc., may carry light fluxes which produce some loss. Bands on the armature core or at the ends may also be the seat of e.m.fs. and will have some loss in them. These losses are difficult to determine, and, in practise, should be eliminated as far as possible.

Full Load Losses

It is evident from the foregoing that the no-load core losses are dependent upon so many variable conditions that there can be no great accuracy in predetermining such losses unless all the details of construction, material, treatment, etc., are known for each individual machine. The impossibility of accurate calculation is shown by the fact that the individual machines built on the same stock order will vary considerably from each other, especially in certain types.

While the no-load losses are difficult to predetermine, the full-load losses are still much more difficult to calculate, as will be shown in the following rough analysis. Here, the effects of flux distortion by the armature magnetomotive force tend to exaggerate the pole face losses and those in the armature copper, which are the two relatively large losses which are most difficult to calculate at no-load. Also commutation and brush losses, due to load, now enter into the problem. The individual core losses may be considered briefly as follows:

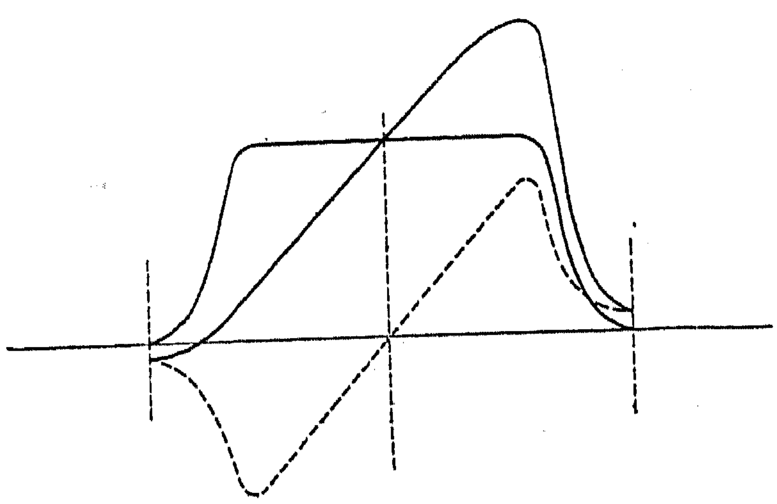

Fig. 5

Armature Ring Loss, with Load. This loss should not change greatly with load, provided the total flux at load is practically the same as at no-load. Under this condition a variation in the distribution of this flux is about the only factor which should produce any material change in loss. The full-load field form may be illustrated by Fig. 5. It is evident from this figure that the flux is now crowded toward one pole edge and, therefore, the major part is concentrated in a narrower space. The average length of the flux path may, therefore, be somewhat greater than at no-load, but in some cases this may tend to distribute the flux more uniformly through the depth of the ring. However, where the flux enters the core at the base of the teeth there will be slightly more crowding and, therefore, somewhat increased loss. Taking everything into consideration it would appear that, in general, the armature ring loss can be considered as practically constant with constant total flux and speed, independent of the variation in load.

In variable-speed and adjustable-speed d-c. machines, the armature ring loss may vary over a wide range due to changes in total flux and speed. Such cases are difficult to calculate with any degree of accuracy, although no more so than other losses in the same machines.

Armature Tooth Loss, with Load. As shown by Fig. 5, the tooth flux density at one edge of the pole is decreased and at the other edge is increased when the field flux is distorted by the armature magnetomotive force. The increased density in the armature teeth means increased iron loss and, if the distortion is very great, the increase in tooth loss may be very large, being in some cases even doubled or trebled, compared with the no-load tooth loss. No direct rule can be given for the calculation of this loss, except that it may be determined approximately by calculating the flux distribution with load and thus determining the flux densities in the teeth.

In variable-speed and adjustable-speed machines, particularly in the latter, the tooth loss with load will be affected very considerably by changes in both speed and total flux. In variable-speed machines of the series type, reduction in speed usually accompanies increase in total flux, so that, as regards the losses, one effect partly neutralizes the other, so that the increase in tooth loss with load may be less than in a constant-speed machine. In adjustable-speed machines, however, especially in those of constant horse power and constant voltage, the tooth losses will vary over a very wide range with change in speed. Here, the armature magnetomotive force is constant (assuming a constant horse power) and the field flux is varied from a maximum value at lowest speed to one-quarter value at four times speed, assuming a four-to-one range. The total flux, therefore, varies inversely as the speed and the two effects should nearly compensate each other, as regards losses, if it were not for the variation in flux distortion. At lowest speed, with considerable saturation in the pole horns and armature teeth, the armature magnetomotive force, even if relatively large compared with the field magnetomotive force, may not produce very large distortion, so that the tooth loss is not increased excessively over the no-load tooth loss. However, as the field is weakened, the armature magnetomotive force remaining constant, the distortion is relatively increased, so that the peak value of the distorted field may remain almost constant in height. As the armature tooth losses are dependent

upon the peak value of this field, then obviously the combined effect of this field and the increase in speed will mean very greatly increased tooth losses. With very low field magnetomotive force, the distortion may be so great as to give a double peak, as indicated in Fig. 6. This double peak gives, to some extent, the effect of a double frequency and thus further increases the loss.

Eddy Currents in Copper. When the field form is distorted, with load, the ampere-turns in the teeth at one pole corner are greatly increased, while those at the other corner are decreased. Therefore, there will be an increased loss in the copper at one pole edge and a decreased loss at the other pole edge. However, as this loss at high inductions will vary almost as the square of the ampere-turns in the armature teeth, it is evident that the reduction in the loss at one pole corner may be small compared with the increase in loss in the copper at the other pole corner. The resultant loss can be calculated approximately by using the formula already given for no-load conditions, but with the ampere-turns in the teeth based on the load conditions. This would give a loss corresponding to no-load with the maximum induction in the teeth raised to peak value with load. This would include losses for the two pole corners; therefore, the result should be halved, as the peak density occurs at only one pole edge.

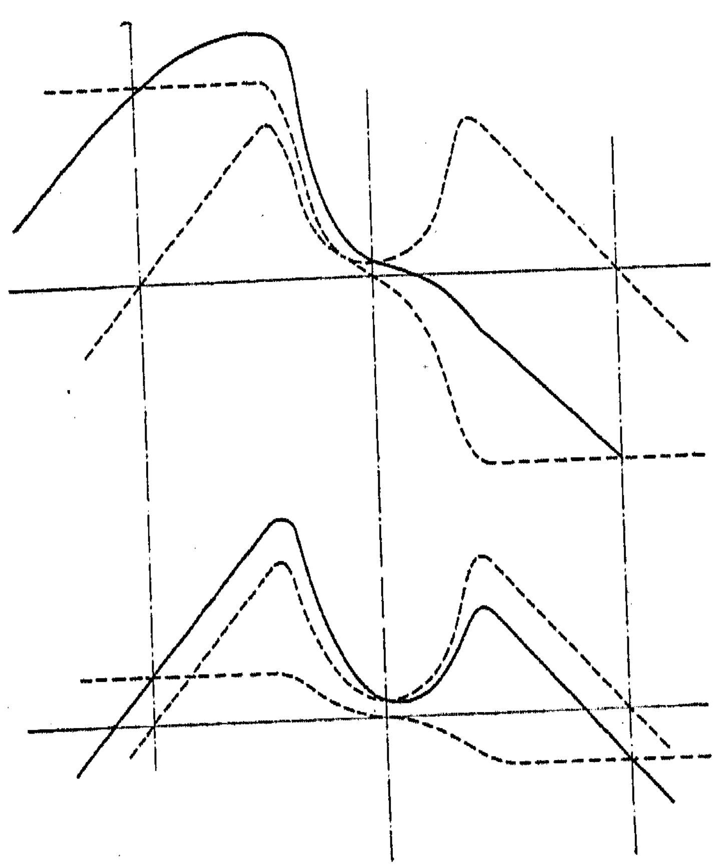

FIG. 6

If the empirical formula given for the copper loss represents the facts, even to a roughly approximate degree, the results are very startling when applied to some of the old-time machines. The calculations show that in some cases the eddy current copper loss at heavy load was several times greater than at no-load. This should be true, but to a much less extent, in more modern types of machines. The results indicate that in many cases there would be considerable gain by reducing the field distortion through high saturation in the pole face, pole horns, etc. This saturation, however, would have to be

so arranged as to give the most beneficial field distribution with load, and haphazard methods of cutting off pole corners, without regard to the field form with load, would have to be avoided. In fact, in the past, the cutting away of pole corner laminations, in many cases, has been largely for the purpose of improving commutation, and not to obtain the best field form with load.

Pole Face Losses, with Load. The pole face losses will obviously be affected locally by change in the flux density in the air gap or at the pole face. Field distortion will tend to increase the loss at one pole corner and decrease it at the other. The increase will usually considerably exceed the decrease, but the resultant will not be increased in anything like the same proportions as the copper eddy current losses under the pole corners are increased with load. A rough approximation for the increased iron loss could be obtained by comparing the squares of the densities, at several points along the distorted field form, with the squares of the densities of the no-load field form corresponding to the total induction.

As the increase in pole face losses with load will, in some instances, be considerably less than the increase in the eddy current losses, it might be advantageous in such cases to decrease the field distortion by pole face saturation, even at the expense of increasing the no-load pole face losses. For example, if, in an extreme case, the air gap were decreased 20 per cent and the air gap ampere-turns thus gained were expended in suitably saturating the pole face material, then the full-load field distortion might be much less than with the larger gap, with the same total field magnetomotive force. The no-load eddy current copper losses would be practically unchanged, while the no-load pole face loss would be increased. However, the full-load pole face loss, due to the reduced distortion, might be no greater than with the larger gap, while the eddy current losses in the copper might be very much less than with the larger gap. In consequence, while the total no-load losses would be increased somewhat, the full-load loss would be smaller than before, and the carrying capacity of the machine would be actually increased. This would apply, however, only to those machines where the no-load eddy current and armature tooth losses are relatively high and where the distortion is rather large with load.

Stray Losses. When the machine is carrying load, the stray

losses given under the no-load conditions may also exist and at the same time some of these may be greatly exaggerated. Also, other losses may appear which are not found at no-load.

Copper loss due to short-circuiting the armature coils in an active field will sometimes be more pronounced than at no-load, particularly in non-commutating pole machines in which the brushes are shifted into an active field to produce commutation. This field, as a rule, will only be of proper value to produce proper commutation at some definite load, while at other loads there may be very considerable local currents in the short-circuited coils, which may produce loss.

As the main field flux is crowded toward one pole corner and the field form becomes more pointed in shape, the effect of variable reluctance in the air gap may become more pronounced than at no-load, and, therefore, pulsations of the main field flux may cause more loss in the short-circuited armature coils.

Stray fluxes from the main poles will be distributed differently from the no-load condition and the densities of these stray fields may be considerably higher at certain points and thus give increased losses.

Additional losses at full load may be due to fluxes set up by the magnetomotive force of the armature winding itself when carrying load. For instance, the armature winding will set up magnetic fields, through the end windings, which fields are fixed in space, in a rotating armature machine. Bands or supporting parts, or other solid metal, rotating with the end winding, may cut these stationary fields or fluxes, and thus losses may be set up which are a function of the load.

Another source of loss at load may be found in the operation of commutation itself. A magnetic field or flux is set up by the armature winding across the slots from one commutation zone to the next. At the point of commutation this flux is reversed in direction with respect to the armature conductors, and, therefore, there will be local currents set up in the armature copper itself, due to this action. This, however, should be more properly charged to commutation loss rather than to armature core loss.

The above covers the principal core losses in direct-current machines. It was the original intention to analyze the core losses in the various types of rotating machines, but it soon developed that the subject was too extensive for the scope

of this paper, therefore it was limited to d-c. machines only. However, many of the conditions which hold for d-c. machines also apply, to a certain extent, to many other types. In addition there are losses in d-c. machines which are relatively large compared with those in other apparatus, due to the fact that the tooth saturation in d-c. machines is frequently carried much higher than in other apparatus.

The foregoing treatment of core losses is qualitative rather than quantitative, and it deals with the simpler phenomena only. It omits some very complex conditions, such as the effect of pulsations in flux superposed on high densities, displaced minor hysteresis loops, etc., which mean additional losses. The principal object of the paper is to give a better idea of the possibilities and impossibilities of the problem of core losses.

Discussion on "Iron Losses in Direct-Current Machines" (Lamme), Schenectady, N. Y., March 7, 1916.

H. F. T. Erben: I agree with Mr. Lamme's statements that iron losses may be approximated with extreme accuracy but these approximations must be based upon past experiences. Mr. Lamme calls attention to the extremely distorted wave form often encountered in variable speed motors and instances Fig. 6 of the paper as being a typical case. While the field form as shown in Fig. 6 is a fair representation of the conditions that may be met in a three to one variable-speed motor, distortions of greater magnitude will be encountered if speed variations of four to one or five to one are attempted. I have in mind a four to one variable-speed motor which at no load and full load and maximum speed had field forms as shown in Fig. 1. It will be noted that at full load the field form was so distorted that there was an actual reversal of flux in the leading pole tip and the flux density at the trailing tip was fifty per cent greater than at no load. When one considers that the teeth in the trailing tip under these conditions are well up to saturation and that the armature teeth are subjected to double frequency, due to the reversal of flux, it is inevitable that there will be extremely high losses. Losses due to distortions of this nature can be obviated by either providing compensating windings or by using very large air gaps.

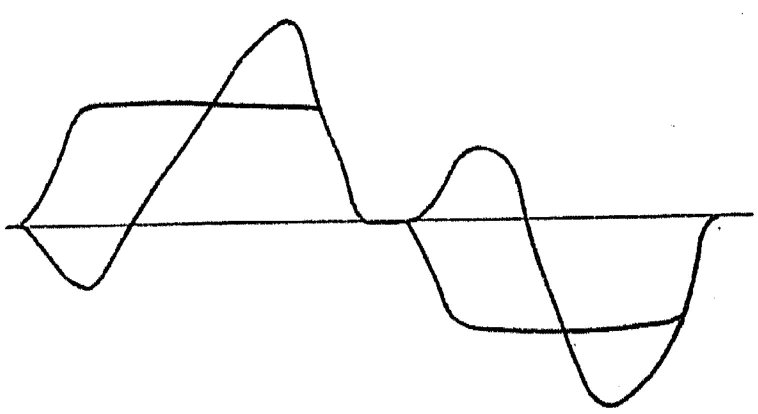

Fig. 1

Generators operating on the multiple-voltage system in connection with mine hoists and rolling mill equipments may have very high core losses under the condition of low voltage and maximum current. The high armature reaction gives rise to an extremely distorted wave form with high peaks. In order to counteract this condition, compensation is usually employed in generators of this type.

Mr. Lamme's paper has only touched upon losses in non-commutating pole machines. In commutating pole machines there is present a loss which is absent in non-commutating pole machines, namely the eddy current loss in the conductors directly under the commutating poles. The flux necessary to produce commutation may be of sufficient magnitude to cause appreciable eddy current losses in these conductors.

Generators and motors in which compensating windings are used are subject to core losses which are not inherent to machines of the commutating pole type. These losses arise through the variations in total flux, caused by the coincidence of the teeth in the armature and pole faces. Although extreme care may be

exercised in arranging the relative position of the two sets of teeth it is almost an impossibility to get any combination of teeth which will not give rise to slight pulsations in flux. Any variation in the magnitude of the tooth flux will give rise to eddy current losses in both the armature conductors and in the conductors used in the compensated winding. I have cited these cases merely to show the extreme complexity of the problem which faces the designer in attempting to make a true estimate of the core losses of machines of modern type.

W. S. Moody: Transformers have no such percentage of losses to contend with as Mr. Lamme has shown us to exist in the case of generators and motors: yet the stray losses in a transformer are by no means negligible.

Most of the different kinds of stray losses which have been mentioned, exist to a minor extent in a well designed transformer and may easily be of a serious amount in a poor design.

If a given quality of sheet steel is made up into a ring shaped core, each lamination perfectly insulated from the others, the minimum loss that possibly can be obtained will result from alternating magnetization. Just as soon as one departs from this simple elementary form of magnetic circuit, the losses increase. The ring cannot even be made into a rectangle of the same cross section and mean length without an increase in the losses. If there are joints either interlocking or butt, increased losses come from the more or less cross flux that results. Again, cross flux gives stray losses when there is a different cross section in different parts of a transformer's core.

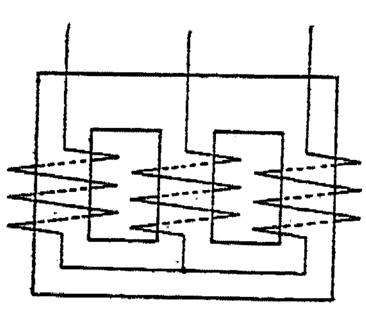

FIG. 2

A transformer core may have another kind of stray loss when the core carries multi-phase magnetization. In the common form of three-phase core as shown in Fig. 2, there is developed in parts of the core not covered by the windings multi-phase flux of a rotating character, which very greatly increases the losses in the iron in this part of the magnetic circuit.

The absence of air gaps and the fact that cores can be built without machining, are the principal reasons why the stray losses are less in transformers than in other apparatus.

Assuming the loss in a ring of laminations, which are perfectly insulated to be the minimum that can be obtained with a given grade of iron, transformers having a simple magnetic circuit can readily be built in which the stray losses are not more than 5 per cent, but when complex magnetic circuits are used and three-phase magnetization introduced, the stray losses in a transformer may readily run to 15 or 25 per cent of the normal losses.

Transformers also have stray losses in the copper, but unlike generators and motors, have stray copper loss only as the load comes on, as there is no flux in the wire space, except as result of the load currents.

Small transformers with small conductors have a negligible stray loss in the copper, but it is difficult in large transformers to keep the loss within a negligible amount, and in poorly worked out designs, the stray copper losses may readily reach such figures as have been mentioned for stray losses in generators.

Wm. B. Potter: The efficiency of electrical apparatus is certainly a subject worthy of most careful analysis. As Mr. Lamme has pointed out, there are often eddy losses of considerable moment other than those strictly chargeable to the magnetic circuit. The copper conductors, under conditions which are favorable to the generation of eddy currents, may in themselves have losses, which result in a temperature rise quite out of proportion to that from the useful current for which they have been provided. An extreme case I recall was a railway motor with armature conductors of unusual depth running in a field of high maximum intensity, and with the original solid bar winding the local current in these conductors was sufficient to cause a temperaature rise equal to that calculated for the energy current under full load. The remedy in this case, as mentioned by Mr. Erben, was to split the bars so as to make narrow strips of that part within the core, and criss-cross these strips midway the length of the slot so as to balance the differences of potential between the top and bottom of the conductor. Desirable as it is to improve the efficiency, it is often essential to keep the losses at a minimum because of the heating that would otherwise result, and this is especially true in electrical apparatus where space is of the utmost importance as is so often the case with railway motors. Probably more is required of a railway motor for its corresponding size and weight than any other electrical machine. The space is limited in width by the gauge, in height by the clearances between the vehicle and the track, in length by the wheel base, and it is fortunate that the maximum requirement has a limitation in the coefficient of adhesion between the driving wheels and the rail. The limitations of space for the railway motor are not only severe with respect to heating, but also the design is so compact, so surrounded by running gear, and operated under such adverse conditions that effective ventilation is a much greater problem than with stationary apparatus. A departure from the enclosed design of motor, depending on its external surface for radiation, to later types in which the armature is so designed as to act as a fan giving forced ventilation, has resulted in great reduction in weight and size for corresponding duty. In some classes of service where the conditions are not favorable to inherent ventilation, the use of external blowers as a supplementary feature has been found essential. It is most important that the losses should be eliminated so far as possible, and next of importance is to effectually deal with the losses that cannot be disposed of.

Friend H. Kierstead: Mr. Lamme in his reference to eddy current losses did not bother us with a statement of the peculiar-

ities and erratic characteristics of these losses. I would like to touch upon the erratic characteristics of eddy current losses with reference to a transformer.

Let Fig. 3 be any conducting material being cut by magnetic flux. Then an eddy current will flow as is indicated in this figure. We can think of this conducting material as being the secondary of a transformer. Now, if its resistance be very high, it acts the same as the secondary of a transformer that is open circuited. If its resistance be very low, it acts the same as a short circuited secondary. The losses in the material due to the eddy currents will be affected by the flux density, by the frequency, by the shape of this conducting material and by its specific resistance. Eddy current losses are equal to $\frac{E^2R}{R^2 \times X}$ where E is eddy voltage, R is the resistance of the eddy circuit, and X is the reactance of the eddy circuit.

Now if the density of the flux that cuts the conducting material in Fig. 3 is changed, then, inasmuch as the only thing that is affected in the above formula by the density is the voltage, the eddy loss will increase with the square of the density, because the voltage is directly affected by the density.

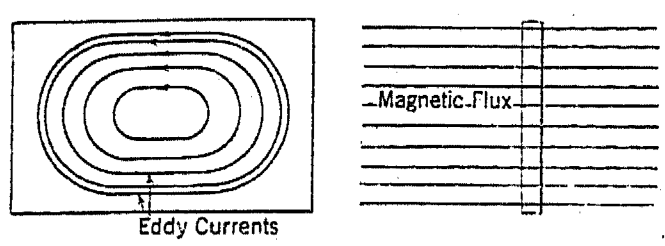

FIG. 3—PLAN AND END ELEVATION OF ANY CONDUCTING MATERIAL BEING PIERCED BY A VARYING MAGNETIC FLUX

Now, if the frequency be changed, then the corresponding change in the loss depends upon the relative values of X and R. If X be very small, as compared with R, the loss is equal to $\frac{E^2}{R}$ and an increase in frequency will increase the voltage, but will not affect the resistance. Therefore, when the reactance of the eddy circuit is small in comparison with its resistance, the eddy loss varies with the square of the frequency.

Take the other extreme, letting the resistance be very small as compared with the reactance, then the loss $= \frac{E^2R}{X^2}$ in which the eddy reactance and the eddy voltage vary with the frequencies, to the same extent. In this case, the eddy loss is not affected by the change in frequency.

An illustration of the former case is in the laminations in the iron of the transformer where the reactance of the eddy circuit is very low and the resistance is comparatively high. An illustration of the second case is in the short circuited transformer where the resistance of the winding is very low in comparison to the reactance, and in this case the losses in the winding do not change greatly with the frequency.

Let us consider now how these losses change with the dimensions of the conductor. Let the conducting material in Fig. 3 become greater in extent, in such way that the flux cutting it also increases. Then the eddy voltage increases as the conductor increases, and so also does the reactance to the same extent.

Now, if the reactance is small in comparison with the resistance the loss $= \dfrac{E^2}{R}$ and since the eddy voltage increases and the resistance decreases with increase in the cross-section of the conducting material, the eddy current losses increase greatly as the cross section of the conducting material increases.

Now, if R be small in comparison with X, the loss $= \dfrac{E^2 R}{X^2}$ and E and X are increasing together, and R is decreasing. Then the eddy losses are decreased by increasing that conductor.

The eddy losses are influenced by the specific resistance. If the specific resistance of a given conductor is changed without changing anything else, then neither the eddy voltage or the

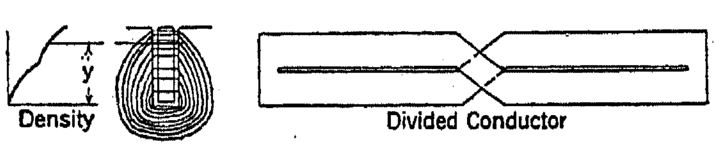

FIG. 4

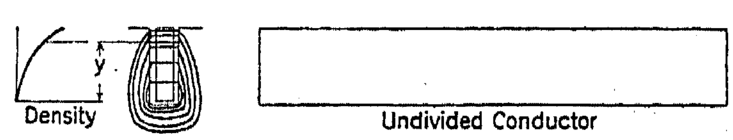

FIG. 5

DIAGRAMS OF FLUX DENSITY

reactance is affected. Therefore, if the reactance be much greater than the resistance, the loss $= \dfrac{E^2 R}{X^2}$ and the eddy losses increase with increase in specific resistance directly, but if the resistance is great in comparison with the reactance, then the loss $= \dfrac{E^2}{R}$ which shows that eddy loss is decreased by increasing resistance.

Departing from above analysis, and taking up the divided conductor in the slot-wound machine. Reference was made to a d-c. machine. Fig. 4 shows such a divided conductor in a slot.

In a d-c. machine where the eddy loss in a conductor is not created by the current which flows through it, but by flux which is independent to a great extent of the current in the conductor, this dividing reduces the loss, but in the case where the eddy current is produced by flux, which in turn is produced by current flowing through the conductor, dividing the conductor may not reduce the loss. Let the field produced by current flowing through the conductor be as indicated in Fig. 4. Now if the conductor were not divided, as is indicated in Fig. 5, then the

greater portion of the current would flow in the top of the conductor and the average density of the flux cutting the conductor would be reduced. However, since the conductor is divided, the same amount of current has to go through the bottom as goes through the top. Therefore, inasmuch as half the current is forced to stay down near the bottom of the slot then the average density is greater than in the undivided conductor and the difference increases with frequency, and therefore the loss in the divided conductor may be greater than it would be if it were not divided, providing the frequency be high enough.

While working under the direction of Mr. H. M. Hobart, we had a problem to increase the loss in an induction motor at starting so as to get greater starting torque, and we actually made up test models to test the losses in the divided and undivided conductors, and we found when the frequency was low the undivided conductor gave greater loss, but when the frequency was high, the divided conductor gave greater loss. It depended upon the depth of this conductor and the frequency. As I remember, when we made the conductor three inches deep, and had 60 cycles flowing through it, the divided conductor gave greater loss.

H. M. Hobart: Mr. Lamme brought out very clearly that there is an irreducible minimum of inaccuracy in predetermination of characteristics. For instance, he mentions in his paper that two machines built on exactly the same specifications, with exactly the same tools, may vary in core loss by 20 per cent.

If Mr. Lamme's paper had not been confined to a discussion of iron losses, if he had touched on commutation, or on regulation, or on the predetermination of temperature rise, or on anything of that sort, the limits which he would have shown for the irreducible minimum of inexactness would probably have been expressed in larger figures than 20 per cent.

Mr. Lamme's assertion relating to 20 per cent inexactness was with respect to the no-load core losses, and he pointed out that it was not exclusively the iron loss, but that there were often also losses in the copper conductors which were included in that expression.

It is a fact that in the completed machine these no-load losses are almost always at least three or four times the loss (reduced to loss per ton) which would be obtained in a test made on a laboratory sample. Transformers constitute an exception; in their case there is no such large multiplier, but even there we do not get down to the losses measured on the test samples.

In machines where the greatest care is taken to keep these losses down, for instance, in induction motors, the multipliers are not so great as in other types.

Mr. Potter alluded to the difficulties concerning weight of, and space occupied by railway motors. I have plotted many curves from factory tests to obtain the factor by which to multiply the laboratory loss (the loss of the test sample), in order to

obtain the loss in the actually completed machine, and that multiplier was larger in railway motors than it was in any other kind of machine. In induction motors the multiplier is reasonably low. In a-c. generators it is decidedly high. These statements relate to the no-load losses.

When we come to the load losses, the observed idiosyncrasies are, of course, all really based on physical laws; such as those to which allusion has been made in the paper; absolutely simple physical laws always being obeyed; but there are so many of these laws that we cannot keep track of them, and at load the losses are often much greater than we estimate. The simple old fashioned efficiency, in which we placed so much faith, is often distinctly higher than the efficiency realized in practise. It is simple enough to measure the efficiency to almost any degree of accuracy, if there is money enough available to spend on the test, but in commercial transactions you cannot arrange for tests that cost as much as, or much more than, the machine itself, and we have to resort to empirical allowances for the various obscure losses.

We are all familiar with the new Standardization Rules issued by the American Institute of Electrical Engineers; the American Rules. A prime mover in creating these Rules was the author of the paper of the evening. Mr. Lamme steadily advocated conservatism in the drafting of these Rules. If I remember rightly, the first suggestion of the plan underlying the "Conventional Efficiency" came from Mr. Lamme. He realized that we could rarely make these laboratory tests which would give the true efficiency, and the only reasonable commercial thing to do was to make sensible assumptions for some of these obscure losses, and he always said—"Let us make these allowances large, let us make them such, that as far as we can foresee, they are certain to at least, cover these actual losses," and so we have in the Rules certain allowances, and it has been the aim of the Standards Committee, that the so-called conventional efficiency, following the recommendations of the Rules, will generally be fully as low as the true efficiency at which you could arrive if you were to make the expensive tests which would be necessary.

Mr. Lamme referred to the subject of temperature rise and I believe it is allowable to make further allusion to the matter. The previous Rules were of some use in this respect; they would give us some rough notion of what the temperature of the parts of the machine might be. As the years advanced, we gradually accumulated convincing evidence that the so-called actual hottest spots in the machine were often far and away above the temperature you obtained with thermometers. Mr. Lamme's attitude was: "Let us recommend certain methods of getting at the very highest temperature, make a clean breast of it, let everybody know that these machines are running at such and such a high temperature." Consequently it was necessary to readjust the temperature limits, so as to make things square up.

That was a very good plan. It recognizes the high plane which should be occupied by engineering.

There is no use in figuring efficiencies higher than they really are. There is no use in employing ideal but unattainable curves in estimating core losses. Let us take a curve which will be sure not to leave us in the lurch. Do not let us employ the ideal curves and say—" This is the predetermined temperature rise in this machine," or " this is the predetermined efficiency of this machine," or whatever it may be, and then never realize such results.

I should like to call attention to a letter which very opportunely reached me today. I thought it was so relevant to this particular subject that I would refer to it. It is from a British engineer, Prof. Miles Walker. He alludes to the A. I. E. E. Standardization Rules, in paragraphs 452 and 453. These paragraphs define the no-load losses. The letter was so appropriate to the paper, and so thoroughly corroborates the general attitude that Mr. Lamme has emphasized, that I thought it would be interesting to refer to it. In reference to these paragraphs Prof. Miles. Walker says:

" Under the heading 'No-Load Core Losses,' of course this refers to all the losses usually included in an 'iron loss test,' and it would be well to have a statement in the Rules that these include all eddy current losses in armature conductors and frame which occur at no load. There is a good deal of evidence on some classes of machines that a *very large proportion* of the no-load losses are not core losses."

William J. Foster: Several years ago an alternator was built that was three or four times as large as anything previously attempted—it was a vertical shaft machine; the weight of the core was great, and the clamps were made much stronger than ever before. The machine was put together with great pressure, to say nothing about the weight of the core itself, which exerted great pressure on the lower part of it. When that machine was tested we were disappointed in the efficiency, as the guarantee had been high and the calculated efficiency was high. It occurred to some of us inasmuch as every element in the design was favorable to a very low iron loss such as narrow slots with respect to the air-gap and reasonable magnetic densities, it might be due to the fact that the core was not really laminated as we thought, and so the second core was put up with considerably less iron in it. This core was tested without putting the regular winding in, but simply a potential coil, so we knew when we had the normal magnetic densities. We found a decided improvement in the loss, something like thirty or forty per cent.

Then we started in to put in more and more iron, and got back to where we were in the first instance. In that particular case we came to the conclusion that we did not know how to insulate our laminations for that kind of work. We then started in to develop a better method of insulating.

Confining ourselves strictly to the iron losses, I am a great believer in the proper lamination of the poles where we build with open slots and have non-magnetic retaining wedges. There, again, in my experience we have had just as great surprises in the old days as in the case of this core that was put together with too great pressure for the insulation that was used. There is always, in the case of revolving field alternators where it is necessary to look out for the safe mechanical structure, a temptation to use laminations in building up the poles that are too thick to give good results in the matter of the core losses. We have gotten in the way of using core loss constants with reference to the product of several factors, such as the thickness of the laminations, the tooth frequency, the breadth of the slot and length of the air-gap.

In speaking of iron losses, as confused with eddy current losses in the conductors themselves,—an interesting case, came under my observation in connection with a turbo-generator, of about 15,000 kw. which had a current something like 900 to 1,000 amperes, which we had to handle in a single circuit. The problem first came up in connection with a 25-cycle generator which was developed with a certain conductor, that proved to be an excellent machine in all respects, having high efficiency and low heating, the temperatures being determined by temperature coils embedded in the heart of the slot. By a little slip, or a little forgetfulness, you may say, the same conductor was put into a machine of practically the same capacity, but 60-cycles, where there were just three or four factors differing enough to make that second machine an impossible one as far as meeting the temperature guarantees were concerned. The conductor was laminated, with every strand insulated throughout the entire length. The winding consisted of two conductors per slot with connection clips at both ends, which solidified or short-circuited all the strands of the conductor. In the case of the 25-cycle machine, the core was relatively short and the pole pitch large. The length of the core represented the e. m. f. or one factor in determining how much current was circulating between the top and the bottom of that conductor, while the total length of conductor represented the resistance or the other factor. The current in one case was two or three times that in the other, and the eddy losses were several times, six or seven times as high in one machine as in the other per unit length of conductor. The consequence was in the first machine they amounted to a reasonable percentage of the legitimate I^2R loss, say 20 or 30 per cent, and in the other case they were so large as to raise the temperature to a dangerous point. A change had to be made in that 60-cycle machine. The 25-cycle machine is still operating,—a number of them,— with very conservative temperatures. That was simply an instance of oversight in designing.

Joseph L. Burnham: As Mr. Lamme has stated the "treatment of core losses is qualitative rather than quantitative and it

deals with the simpler phenomena only," although these phenomena are of major importance. The value of the paper seems to me not to be so much in the methods of calculation developed as in calling attention to the conditions to be avoided. The calculations are rather complicated for practical work and depend too much upon known characteristics of the material (which cannot be depended on) and also upon experience which can only be obtained from the results of many tests.

The previous speakers have mentioned the advantages to be obtained from the use of compensating windings but have not mentioned that there are other sources of loss induced by these windings which are very similar to the losses caused by variations in flux density as described by Mr. Lamme and represented in his Fig. 2. By the multiplication of the compensating windings made necessary in modern machines of high armature reaction, the space in the pole face becomes crowded so that care must be taken that local densities are not high thus causing unequal flux distributions. Furthermore, the opposing magnetization of the compensating windings and the armature conductors tends to set up a flux around the periphery of the armature, so that, to avoid the bunching of this flux at the pole tips, the reluctance of this path should be made high. If the compensating conductors are not placed quite close to the surface of the pole face, there should be narrow slots in the pole face between the compensating conductors and the pole face parallel to the conductors to increase the reluctance around the periphery of the pole face.

L. T. Robinson: I will add one word to cover the point that Mr. Hobart brought out. I think there may be a little doubt in the minds of some of you as to the difficulties of making iron loss tests agree with the losses computed from determinations made on rings or other samples. I do not think there is any difficulty in arriving at an answer, which is as correct as you can arrive at anything where the material itself is subject to so much variation.

You cannot, certainly, predetermine the core losses closer than you can know the properties of the material which you are going to use, and you do not know that very closely. That must be assumed. In cases where it has been possible to know exactly what the material is, it has been possible to get very close. I am sure you could get similar results in other cases, if you knew where the flux went and how much of it went in certain places. As bearing on that point, I notice that certain figures for magnetic flux density have been referred to as 180,000 lines ($B =$ 28,000). This estimate is much higher than I believe it should be. The assumption is no doubt made that whatever flux goes through the armature is bound to go through the teeth. Under the conditions of use the permeability of these teeth is very low, and no doubt a large percentage of the flux goes through the slots.

A. S. Langsdorf (by letter): The best determinations of pole face losses and of empirical formulas for their calculation have been made by operating a machine as a motor and subtracting from the input the sum of the other losses. It is well known that a method which involves the evaluation of a relatively small quantity by taking the difference between two relatively large quantities is liable to considerable percentage error even under the most favorable conditions; and in the case of such a determination of pole face loss the inaccuracy is still further enhanced by the fact that the sum of the "other losses" is difficult to determine because it includes such uncertain items as losses due to flux pulsation, brush contact, eddy currents in armature conductors, and distortion of flux caused by armature reaction.

Considerations of this kind led the writer to the conviction that a reliable determination of pole face loss could be made only by a radical departure from previous test methods and by the development of apparatus that would permit the direct measurement of the pole face loss itself. To this end there has

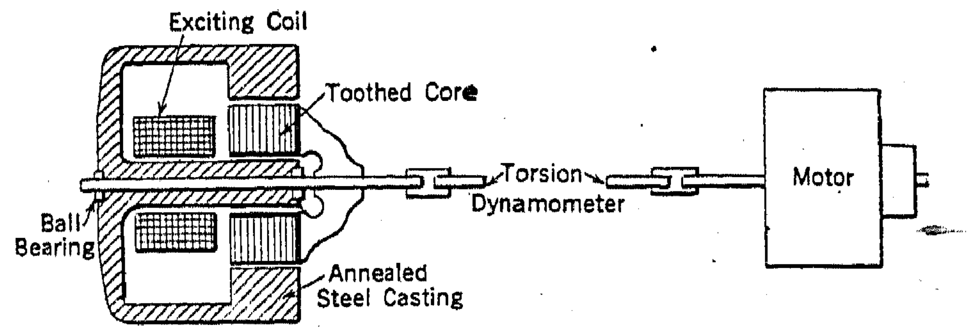

FIG. 6

been designed a special machine built along the lines of a homopolar generator, as indicated in Fig. 6. The frame consists of an annealed steel casting of E section with an exciting coil wound on the central core. In the annular space between the central core and the overhanging outer ring (the pole face) there is centered an unwound, laminated toothed core assembled on a cast iron spider carried by a shaft mounted in ball bearings. The toothed core is driven by an adjustable speed motor through a torsion dynamometer. The only losses that can occur in this machine are the pole face loss and the friction and windage loss; hysteresis is eliminated because of the fact that the core is traversed by a unidirectional, unvarying flux; eddy currents are eliminated provided the flux is uniformly distributed around the gap, a condition that is easy to obtain by accurate centering and which has been shown to exist by careful tests. Friction and windage at any speed can be entirely eliminated by taking as zero reading of the dynamometer that setting which corresponds to the condition of zero field excitation, hence the pole face loss can be read directly.

The apparatus readily lends itself to the following series of tests:

1. *Dependence of the pole face loss upon average flux density in the air-gap.* In this test the speed of the core is kept constant and the field excitation is varied, the value of the gap induction being determined by the reading of a voltmeter connected through slip rings to a piece of insulated wire stretched across the tip of a tooth.

2. *Dependence of the pole face loss upon peripheral velocity of teeth.* In this test the flux density in the gap is kept constant at some convenient value.

3. *Dependence of the pole face loss upon the slot opening.* For this purpose two interchangeable cores have been provided, one having straight open slots, the other semi-closed slots.

4. *Dependence of the pole face loss upon length of air-gap.* After completing series 1, 2 and 3, the pole face is to be bored out slightly and a new series taken, this process being repeated until the air-gap has been increased to a point where the pole face loss is negligible.

5. *Dependence of pole face loss upon material and construction of pole face.* After the completion of the four series outlined above, the overhanging cast steel pole face will be cut away and in its place there will be successively inserted rings of cast iron, and laminated steel.

Although the construction of this apparatus was undertaken some time ago, a long series of mechanical difficulties had to be overcome before the machine could be made to give dependable results. Work on series 1 and 2 is in progress at this writing. The results thus far obtained indicate that the pole face loss varies at a slightly greater rate than the second power of the gap induction, and very nearly as the 3/2 power of the peripheral velocity, in accordance with theory. The writer hopes to be able to present detailed reports at a later date.

B. G. Lamme: Mr. Erben, in his discussion, has referred to certain pole shapes which reduce flux distortion with load and thus lessen or prevent iron losses due to increase in load. However, the arrangements which he has shown are not suitable for reversible operation, especially where there are liable to be very heavy loads with weak fields. For instance, take reversing mills working on the variable voltage system, where there are frequent excessively heavy currents at almost zero field fluxes. In such machines, as a rule, compensating windings are used to prevent flux distortion, primarily to avoid high voltages between commutator bars and to help commutation. Reduction in armature core loss is not a first consideration in such machines, but the compensating winding, of course, does reduce the loss somewhat.

Referring next to the point which Mr. Hobart mentioned, namely, the desirability of admitting that we cannot calculate certain things in electrical apparatus, with any great accuracy; I have always been a believer in the doctrine that if there are limitations to our doing a certain thing, it is much better to

recognize such limitations and admit them, and in that way more progress will be made. If we cannot calculate all the losses in a machine with any great accuracy, it is better to analyze them, as far as possible, and find where and why accuracy is not practicable. We should recognize what we cannot do and what the real limitations are and we are then in a much safer position than if we go ahead blindly. For many years the Standardization Rules of the American Institute of Electrical Engineers were very apt to mislead the public. For instance, in the problems of temperature measurements, practically everybody outside of the manufacturing companies thought that accurate temperature determination was a practical condition. One of the great things we did in the last revision of these Standardization Rules, was to show the possibilities of inaccuracy in temperature determination. We openly admitted that temperature measurements as carried out practically, were only approximations, and, in my opinion, in taking this stand we really took a long step forward in the art. The same holds true in regard to efficiency. If we know that we cannot measure it exactly and will tell why we cannot do so, then by so much we advance the art. The same holds true with core losses. However, there is this difference between core loss determination and the other instances just cited, namely, core losses can be predetermined with very considerable accuracy, by what may be considered as empirical methods. These calculations, however, may be considered more in the nature of estimates than true calculations.

The point which I wish to bring out in particular is, that if we know wherein inaccuracies are liable to occur in our calculations, and also know how much the errors are liable to be, in new classes of work in particular, then we are in a position to allow sufficient margin of safety. The difference between experience and inexperience in a designer, is often indicated by this margin of safety.

Presented at the 319th meeting of the American Institute of Electrical Engineers, New York, March 10, 1916.

THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY REVERSED CURRENT ON ELECTROLYTIC CORROSION

BY BURTON MCCOLLUM AND G. H. AHLBORN

ABSTRACT OF PAPER

This paper describes experimental work done to determine the co-efficient of corrosion of iron and lead in soil with varying frequencies of alternating or reversed current with 60 cycles per second as the highest frequency and a two-week period as lowest—some d-c. tests being made as a check on the methods. The results show (1), that a decrease of corrosion occurs with an increase in frequency; (2), that the corrosion is practically negligible below a five-minute period; (3), that there is, a limiting frequency above which practically no corrosion occurs; (4), that certain chemicals affect the natural and electrolytic corrosion of the two metals quite differently; (5), that the loss of lead in soil on direct current is about 25 per cent of the theoretical loss; and (6), that alternating or reversed current with as long periods as a day or a week would in the case of iron materially reduce the damage to underground structures.

The importance of these results grows out of the fact that there are large areas in practically every city in which the polarity of the underground pipes reverses with periods ranging from a few seconds to an hour or more due to the shifting of railway loads. The investigation shows that the corrosion under such conditions is much less than has generally been supposed.

I. INTRODUCTION

THE TERMS "electrolytic corrosion" and "electrolysis" have been used to designate corrosion caused by the discharge of electric currents which entered the metal from outside sources. In this paper the term a-c. electrolysis applies not only to electrolysis from ordinary alternating currents of commercial frequencies, but also to alternating currents of much longer periods, such as several minutes or even a day or longer. Alternating currents of such long periods are very common on portions of underground pipe systems of practically every city due to the continual shifting of railway loads which causes the pipes within a large area, commonly called the neutral zone, to continually change their polarity with respect to the earth. In this paper the term "coefficient of corrosion" is frequently used in connection with the corrosion

of an anode. This factor is the ratio of the actual corrosion observed to that which would have occurred if all of the electrode reactions determined by Faraday's law had been involved solely in corroding the anode. Thus if the theoretical corrosion in any case was 100 grams and the observed corrosion 46 grams, the "coefficient of corrosion" would be 0.46. This is sometimes called "efficiency of corrosion."

Importance and Scope of the Present Investigation

Since most of the electrolysis which occurs is due to stray currents from electric railways, and since only a small percentage of these operate with alternating current, it might seem at first thought that a-c. electrolysis is of rather infrequent occurrence, and that the problems connected with it do not deserve much attention. However, in addition to the railways which use alternating or reverse currents as motive power, such currents often result as an incident of railway operation. These occur not only in the ordinary negative systems of railways as mentioned above, as the trolley load shifts from point to point on the track with the movement of the cars, but they occur to a greater extent and in a much larger territory in the case of negative return systems in which insulated negative feeders are used. In such systems the potential differences between pipes and tracks can be greatly reduced, but this is accompanied by a large increase in the area of the so-called neutral zone in which the polarity of the pipes is continually changing from positive to negative. With certain types of three-wire systems which are now being seriously considered in some places for the prevention of electrolysis, there will be large areas in which the polarity of the pipes will fluctuate between small positive and negative values. It has also been proposed that with the usual type of return that the trolley be made alternately positive and negative on succeeding days or weeks. All of these methods would have the effect of reversing the current flow on underground structures, and the period of the cycle would vary from a few seconds to a day or longer. Moreover, the frequent grounding of 60-cycle lighting circuits permits a certain amount of leakage from those systems, and the corrosion produced, especially in case of accidental grounds on other parts of the system, would be of considerable importance if alternating current gave rise to serious corrosion. It is therefore of great practical importance to determine the extent to which periodically reversed currents

of these long periods will produce corrosion on subsurface metallic structures.

Work of Previous Investigators

A number of writers have advanced theories concerning laws governing a-c. electrolysis and a considerable amount of experimental work has been done with frequencies of 25 to 60 cycles. One writer, discussing the phenomenon from the standpoint of the decomposition of the electrolyte,[1] arrives at certain conclusions: (1), That the quantity of electrolyte decomposed by alternating current is less than by direct current; (2), that it is proportional to the electrode current density; (3), that there is a limiting electrode current density below which no decomposition of the electrolyte occurs; (4), that the quantity decreases with an increase in the frequency of alternations, and that there is a limiting rapidity of alternation above which there is no decomposition. Conclusions (1), (3), and (4) seem borne out by the experimental work described later.

With reference to the dynamic characteristics of electrolytic cells, several writers have determined by experimental work,[2] chiefly with the oscillograph, that such cells affect the wave form. As one writer states, the chemical polarization in the cell causes it to behave as a variable condenser with a resistance in parallel and in series.

With a very special set of conditions one experimenter[3] has noted an amount of corrosion of the electrodes varying from zero to 35 per cent, with 60-cycle current, and he arrives at the conclusion that the corrosion is practically independent of the current density of the electrodes and temperature; and also that stirring of the solution has no effect. He states that the corrosion does depend on the condition of the electrode surface but does not attempt to state the principle of this variation.

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1. Dr. Guglielmo Mengarini, *Electrical World*, Vol. 18, No. 6, p. 96., Aug. 8, 1891.

2. Ruchinstein, D. Electrolysis with Alternating Current Dynamic Characteristic of an Electrolytic Cell. *Zeitschrift für Electrochemie* December 1, 1909; LeBlanc, M. The e.m.fs. of Polarization and their Measurement by the Oscillograph. Deut. Bunsen Geselschaft. No. 3. Alternating Current Electrolysis Use of Oscillograph in Connection with Polarization. *Zeitschrift für Electrochemie* 11, 707, 1905.

3. White, G. R., Alternating Current Electrolysis with Cadmium Electrodes.

Experiments of more practical importance to the engineering world were conducted in 1905.[4] Twenty-five-cycle current was impressed on iron and lead pipes buried in soil and it was found that the corrosion was practically the same as that due to the soil alone. No figures of exact losses are given. Alternating current of 25-cycle frequency was impressed on lead and iron plates in salt solution and direct current was impressed on other plates in a similar electrolyte and it was found that the loss was negligible for the alternating current and very large for the direct current.

Only a year or so later a large number of tests were conducted with 25-cycle, 60-cycle, and direct current on iron and lead plates.[5] The conditions were varied by using different soils, salts added to soils, varying the temperature and current density. The results show that although there is quite a large variation in the loss with different specimens and that the 25-cycle losses are uniformly greater than the 60-cycle; these losses never exceed one per cent under normal temperature conditions. The writer notes that some salts, for example, carbonates and alkaline compounds, reduce the electrolytic corrosion of lead plates. He found that an increase of temperature to 40 deg. cent. increases the corrosion to about one per cent. His final conclusions are that a-c. electrolysis is more irregular than d-c. electrolysis, that nitrates increase corrosion and carbonates generally decrease it, but that the effect is not great enough to be of practical use for protecting lead cables; that lead is more readily attacked than iron; that the current density does not appreciably affect corrosion except indirectly by increase of temperature; and that the corrosion increases with a decrease in frequency. He attempts to protect lead specimens by making them negative either by connecting them to a zinc plate or with a small direct current, and finds that the loss is considerably less than with the alternating current alone. He finds that a current of one per cent of the value of the alternating current is sufficient to give practically complete protection, the corrosion in some instances being less than that due to natural corrosion alone. It will be noted in the above experimental work that the different variables employed, such

4. Kintner, S. M., Alternating Current Electrolysis, *Electric Journal*, Vol. 2. p. 668, 1905.

5. Hayden, J. L. R., Alternating Current Electrolysis, TRANS. A. I. E. E., Vol. XXVI, Part I, p. 201.

as current density, chemicals, temperature, etc., do change the action of alternating current, but that in practically no case did the losses exceed one per cent. When we consider the large variation of the electrochemical loss produced by direct current under identical conditions, it is evident that differences obtained between 25- and 60-cycle current are practically negligible.

Purpose of this Paper

The data discussed in this paper were obtained as a part of the general investigation of electrolysis conducted by the Bureau of Standards. Its object is not to determine the laws which govern electrolytic corrosion at any one frequency, but to take a standard set of conditions approaching as nearly as possible those existing in practise, that is, wrought iron pipes and lead sheaths imbedded in soil and to determine the corrosion which will occur in the range of frequencies mentioned above, namely, for frequencies ranging from 60 cycles per second to a week or more per cycle. These data will be of material assistance in determining the effectiveness of many of the proposed systems of electrolysis mitigation.

II. DISCUSSION

Preliminary Experiments on Effect of Circulation of Electrolyte

Before beginning the more complete series of tests to determine the effect of change in frequency, a number of preliminary experiments were carried out in order to throw light on certain theoretical aspects of the question under consideration. Theoretical considerations led to the belief that the corrosion of frequently reversed currents would be materially increased by rapid circulation of the electrolyte and diminished by conditions which tended to restrict such circulation. If this were true it was reasoned that in the case of metals buried in soils, in which the circulation of electrolyte is greatly restricted, relatively little corrosion would occur even with periodically reversed currents of long period. Accordingly, a number of experiments were carried out to determine the effect of circulation of the electrolyte on the coefficient of corrosion.

A set of four cells with wrought iron electrodes and a one per cent NaCl solution as the electrolyte were connected in series on 60-cycle current. The electrolyte in cell No. 1 (see

Fig. 1) was stirred by a small turbine and in No. 2 the electrolyte was undisturbed; in No. 3 the electrodes were wrapped with filter paper; and in No. 4 the electrolyte was prevented from mechanical circulation by gelatin. Iron electrodes which were carefully weighed were connected in the circuits and the current was maintained at about a

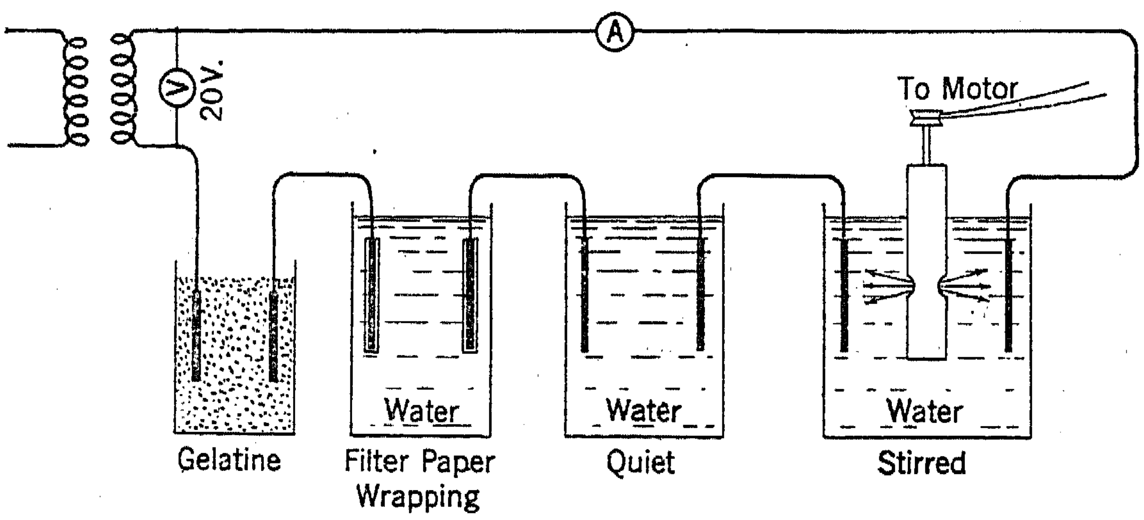


FIG. 1—ARRANGEMENT OF FOUR CELLS

half ampere for nearly 200 hours. At the end of the run the electrodes were again weighed and the loss determined by difference from the initial weight. Based on the theoretical loss, which would have been about 100 grams, the coefficients of corrosion (see Table I) are 0.0034 for the stirred electrolyte;

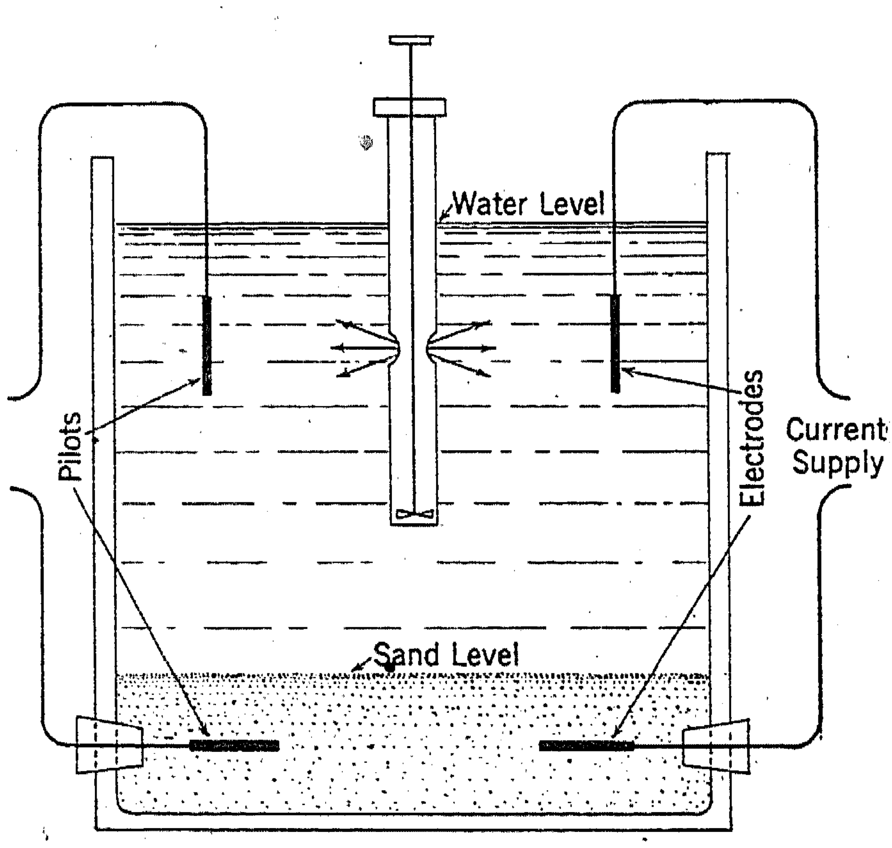


FIG. 2

0.002 in the stationary solution; 0.0009 when protected by filter paper; 0.0007 in the gelatin. It seems evident that the chemical action is not as reversible when the electrolyte is in motion about the electrodes as when stationary. In order to determine this effect more exactly a single cell was con-

nected as shown in Fig. 2. Here there were two electrodes with no current impressed to determine the natural corrosion and two serving as current electrodes. One of these was in the electrolyte stirred by the turbine and the other was wrapped in filter paper and buried in sand saturated with the solution. After correcting for the natural corrosion it was found that the

TABLE I.

EFFECTS DUE TO VARIATIONS IN THE CIRCULATION OF THE ELECTROLYTE

60-Cycle Current
Wrought Iron Electrodes
1 per cent NaCl Solution Electrolyte

State of electrolyte	Total corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred	0.344	96	0.0034
Stationary	0.202	96	0.0020
Filter paper, separation	0.088	96	0.0009
Gelatin	0.074	96	0.0007
Stirred	0.065	160	0.0004
Sand saturated	0.016	160	0.0001

TABLE II.

EFFECTS DUE TO VARIATIONS IN THE CIRCULATION OF THE ELECTROLYTE

20-Cycle Current
Wrought Iron Electrodes
1 per cent NaCl Solution Electrolyte.

State of electrolyte	Total corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred	0.079	144.4	0.0005
Sand, saturated	0.009	144.4	0.00006

coefficient of corrosion was 0.0004 for the upper electrode and 0.0001 for the lower. The results are shown in Table I. The same type of cell was operated on 20-cycle alternating current with the losses as shown in Table II. It will be noted that the loss values are almost exactly the same as those on 60 cycles under the same conditions and in every case are considerably less than 0.005. The same type of cell was placed in a d-c. circuit which was reversed every 24 hours. As might be ex-

pected, the losses were very much greater, as shown by Table III; although the number of ampere-hours was considerably less than that used in the previous experiments. The electrode surrounded by the moving solution had a loss corresponding to a coefficient of corrosion of 0.45, while the other gave 0.32, the difference due to stirring thus being even more evident on the slow reversals than on the high frequencies. If only the current discharged by each electrode as anode were considered, the coefficient of corrosion in the stirred solution was 0.90, and that in the confined electrolyte was 64 per cent.

TABLE III.

EFFECTS DUE TO VARIATION IN THE CIRCULATION OF THE ELECTROLYTE.

24-Hour Reversals
Wrought Iron—Electrodes
1 per cent NaCl Solution Electrolyte.

State of electrolyte	Electrolytic corrosion grams	Current ampere-hours	Coefficient of corrosion
Stirred........................	45.45	97.1	0.45
Sand, saturated................	32.45	97.1	0.32

The foregoing results show that the free circulation of the electrolyte has a pronounced effect on the coefficient of corrosion, and that this effect is greater the lower the frequency of alternation of the current. They show that the low corrosion coefficient on alternating current is not determined solely by the speed of the reactions and the frequency of alternations. A more probable explanation is that the corrosion during any half cycle in which the electrode is anode takes place in accordance with Faraday's law, as in the case of direct current, but that during the succeeding half-cycle when the electrode is cathode a large part of the corroded metal is electroplated back on the electrode. The increased corrosion due to circulation of the electrolyte would be expected under this theory, since the convection currents in the liquid would carry away from the electrode surface a part of the metal that has been corroded during the half of the cycle when the electrode is anode, thus preventing as complete a redeposition during the succeeding half-cycle as would otherwise occur. In particular these convection currents in the electrolyte would bring into contact

with the metallic ions, oxygen or other chemicals which would tend to form insoluble compounds, thus rendering the corrosive process irreversible.

Accepting the above theory, we would expect that in the case of iron or lead buried in soils, in which circulation of the electrolyte is greatly restricted, the corrosive process would be in large degree reversible even with much longer periods of reversal than in the case of liquid electrolytes, and it seemed possible that this condition might prevail even where the period of the cycle is several minutes or longer, as in the case of the polarity of buried pipes in many localities as mentioned above. This was found to be actually the case, as the following described experiments show.

Complete Series of Tests

(*a*) *Arrangements.* With the results of the above experiments in view a more complete series of tests was planned. Since there is considerable variation among individual specimens, it was recognized that quite a number of specimens under each frequency would be necessary in order to get a fair average. The specimens were arranged in cells having two current-carrying electrodes and one specimen subjected only to soil corrosion, this specimen being protected from the flow of current by a glass cyclinder as shown in Fig. 3. In a few cases the effect of adding sodium carbonate to the soil was studied. For convenience the greater part of the tests were made in jars in the laboratory, but a number were made in specimens buried in soil out of doors in order to check the results obtained in the laboratory. The agreement between the results under the two conditions was found to be satisfactory. The entire series is outlined in Table IV.

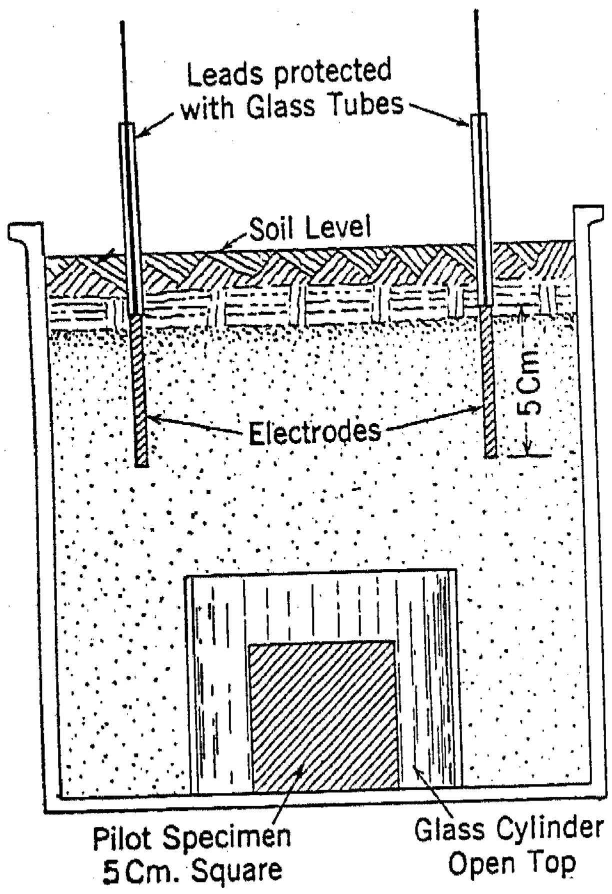


Fig. 3

(*b*) *Electrolyte.* In determining the coefficient of corrosion with different frequencies of current reversal it is desirable to simulate operating conditions as nearly as is feasible in a complete and general test. For this reason soil was selected

as the electrolytic medium rather than water which contains the soluble constituents found to exist in soil by chemical analysis. Conditions of circulation of the electrolyte and the electrolytic transfer in it are very different than in soil. The soil used was natural soil near the Bureau of Standards—a light clay having a resistance of 8000 ohms per centimeter cube at approximate saturation. It will support a good vegetable growth and is a fairly normal soil. Soil from the same locality

TABLE IV.
SUMMARY OF TESTS.

a. Dimensions of Electrodes.

Electrodes	Indoor	Outdoor
Iron	5 x 5 x 0.5 cm.	20 x 20 x 0.2 cm.
Lead	5 x 5 x 0.2 cm.	15 x 15 x 0.4 cm.

b. Frequencies Used and Number of Specimens Used for both Iron and Lead.

Frequency of reversal	Number of specimens — Indoor — Natural Soil	Number of specimens — Indoor — Soil with Na_2CO_3	Outdoor Tests
60 cycles per sec.	18	18	3 large } Iron only.
15 cycles per sec.	18		
1-sec. cycle	18	18	3 " } Iron only.
6-sec. cycle	18		
1-min. cycle	18		
5-min. cycle	18		
10-min. cycle	18	18	
1-hr. cycle	18		
2-day cycle	18		
2-week cycle	18	18	
Direct current	18	18	3
Totals	198	90	9 large

Grand total for iron 297
" " " lead........291
" " " all tests.....588

was used in the experiments described in a previous Bureau of Standards report[6] and a coefficient of corrosion of 100 obtained on iron at a definite current density.

(*c*) *Conditions of the Tests.* Some of the tests were run in the soil out of doors with natural drainage and aeration. Although it was considered very desirable to make a number of such tests, to run a complete series in outside soil would

6. McCollum and Logan; Technologic Paper No. 25. Electrolytic Corrosion of Iron in Soils.

have been very difficult on account of interference by weather, difficulty of getting electrical connections to many electrolytic cells,. and especially the insulating of the various sets from each other, which would be necessary in order to determine the current actually entering or leaving each specimen. The cells used in the inside laboratory tests were 1-gal. (3.8-liter) earthenware jars filled with soil to about 3 cm. from the top (about 3 kg.) kept practically saturated by adding a quantity of distilled water every day. The tops were left open that evaporation and aeration might go on in a normal way.

(*d*) *Chemicals*. Since some soils vary widely in chemical constituents and these may have a pronounced effect on the rate of corrosion, it seems desirable to vary those constituents in the soil which may be expected to affect the corrosion. As indicated by preliminary tests, sodium carbonate (Na_2CO_3) has a very considerable effect on the electrolytic corrosion of both iron and lead; moreover sodium is a common element in soil, as are carbonates; and this combination is quite soluble, which makes it a satisfactory compound to use in the soil, 0.5 per cent being added to certain cells, as shown in Table IV.

(*e*) *Electrodes*. Since iron and lead are the two metals commonly serving as underground electrical conductors exposed to soil they were selected as the materials for specimens in these tests. The above mentioned report shows that the corrosion of different kinds of iron does not differ by large percentages under the conditions of these tests, and since "American iron," which is Bessemer process steel, is obtainable in convenient form it was adopted. This material was fine-grained and quite pure, having about one-tenth per cent carbon and no slag. The lead was commercially pure and on analysis was found to contain traces of tin or antimony. Indoor specimens were 5 by 5 cm. square, the iron being about 0.5 cm. thick and the lead 0.2 cm. thick. The outdoor iron specimens were 20 cm. square and about 0.2 cm. thick.

The mill scale and oxide left on the materials in the process of manufacture were not removed, since it was felt that with alternating current the surface might affect the corrosion considerably more than with direct current. The leading-in wire was soldered to a corner of each specimen and a number stamped on the same corner. It was then weighed and a glass tube put over the lead and the tube was then sealed with pitch and the lead attachment and number covered with the same

material. This type of connection failed in very few instances due to corrosion and the tube and pitch were easily removed with toluol before the specimen was reweighed.

(*f*) *Frequency*. In determining the frequency of reversal of current two things must be considered: first, the frequencies found in practise; and second, the completeness of the series so that a suitable curve could be obtained showing the relation between the corrosion coefficients and the frequency of reversal of current. The standard lighting frequency, 60 cycles is available, and 15 cycles adopted as about the lowest frequency proposed for power work. To obtain the slow reversals a reversing commutator machine was built which is described in detail later. It gave periods of one second, 6 seconds, 1 minute, 5 minutes, 10 minutes, and 1 hour. The short periods of reversal were adopted because reversals of polarity of such frequencies commonly occur in the usual operation of a street railway system as pointed out above. Daily and weekly reversals and d-c. tests were also made. The d-c. specimens serve as a check on the theoretical coefficient of corrosion.

(*g*) *Current Density*. The current density flowing to or from the plates was intended to be such as to produce approximately 100 as the coefficient of corrosion with d-c. electrolysis. This is shown in Technologic Paper No. 25 of the Bureau of Standards above referred to, to be about 0.5 milliampere per sq. cm. for iron and approximately this value was used on both the indoor and outdoor specimens.

(*h*) *Length of Run*. The tests were contined until enough effect was produced to permit of accurate determination of the differences in weight of the specimens before and after test. It was also intended that one of the tests should be continued until a state of equilibrium was reached in the cell; that is, until the rate of corrosion was not changing rapidly as might be the case during the first few cycles of current. Moreover, the cells should not be run to an exhaustion of the soluble chemicals, their concentration being probably closely related to the amount and rate of corrosion occurring on the electrodes. Since the current density is the same in all cases, this rate will depend on the frequency of reversal, and since the coefficient of corrosion is less on the higher frequencies these must run fully as long as the lower frequencies in order to obtain sufficient weight differences. A period of 15 to 20

days has been found to produce sufficient differences in weight, and no indication that the composition of the soil, except that very close to the electrodes, had been changed decidedly.

(*i*) *Accidental Variables.* Other possible variables that received attention during the experiments were maintained as nearly constant as possible. The temperature did not vary widely from 20 deg. cent. there being very little heating by the current at the voltage and current density used. The depth was maintained about 10 cm. below the surface in the indoor tests and about 40 cm. in those outside the laboratory.

(*j*) *Cleaning Electrodes.* After each run was completed it was necessary to remove the end products of the corrosion process, and since they adhered firmly in some cases special methods were necessary. Iron specimens were cleaned by making them cathode on a ten volt circuit in a two per cent sulphuric acid solution, as described in Technologic Paper No. 25 of the Bureau of Standards. This was found to be very effective and did not attack the iron enough to show on the balances used. The lead specimens were cleaned by immersing them in a solution containing 5 per cent oxalic acid and $1\frac{1}{2}$ per cent of nitric acid. The corrosion products became lead oxalate—a white flocculent substance which was easily removed by brushing. It was found in some cases where the amount of corrosion was large and adhered very firmly that this process was very slow and did not remove the corroded products entirely. Unoxidized specimens weighed before and after immersion in this lead cleaning solution were found to have lost less than 5 milligrams, the limit of the balances used.

Equipment

(*a*) *Current Sources.* Sixty-cycle current was obtained from the city power mains, while the 15-cycle current came from a small inverted synchronous converter. Transformers were used in both circuits to raise the voltage so that a number of cells could be operated in series and so that the primary side would be clear of ground. For the slower reversals of current on the indoor tests power was obtained from the regular three-wire lighting busbar and commutated by the machine described below. For the outdoor tests for slower reversals and for direct current a small motor-generator set was used. A no-current indicator was used on the a-c. circuits while a recorder showed what had occurred on the d-c. circuit and those of long period at all times.

(*b*) *Commutating Machine.* The commutating machine through which the intermediate frequencies were obtained consisted of a series of six commutators each having four brushes and two equal semi-circular commutator segments, giving two complete cycles per revolution, driven by gears having such ratios that with the first or highest speed commutator rotating once in two seconds the succeeding commutators made complete current cycles in six seconds, one minute, five minutes, ten minutes, and one hour. This machine was driven by a constant speed motor.

(*c*) *Resistance.* In order to obtain the correct current density discharged from the electrodes the resistance of the circuits had to be varied. This was done in part by placing cells in series in groups and paralleling these groups. Rheostats or tungsten lamps were then used to get final adjustments, but no great effort was made to keep the current discharge at exactly 0.5 milliamperes per sq. cm., since a small variation in current density does not affect the rate of corrosion. Tungsten lamps with their high positive temperature coefficient are very satisfactory for use in such circuits, since within a certain range they tend to automatically maintain the current at a constant value.

(*d*) *Current Measurements.* Observations of current were made every day, and more frequently when the current values were changing appreciably. A standard milliammeter having a resistance of 0.34 ohm was used for all frequencies above one second. For a-c. measurements a thermo-ammeter consisting of a heating element, thermo-couple and millivoltmeter was used. The resistance of this meter amounted to about 7 ohms, and was non-inductive. When this meter was introduced in circuits the effect on the current flow was negligible because of the high resistance of the circuits and it was very easy to correct for this small non-inductive resistance by inserting an equal amount in each circuit when the meter was not in use. This meter was used to measure larger currents in the outdoor specimens by means of a shunt. A suitable ampere-hour meter was not available.

Correction and Reduction Factors

Since chemical corrosion, according to Faraday's law, is proportional to the average current flowing, and since all a-c. values as observed are effective values rather than average,

the current flow has been corrected by dividing the same by 1.11, the ratio between effective and average values of sine-wave current. Since the current flowing with the longer time reversals is controlled by a commutating machine or switch the wave is flat-topped and no such correction is necessary. However, the current was off when controlled by the commutating machine, 6 or 7 per cent of the time and this correction was applied to all such values. In order to correct any error due to a possible difference in the length of succeeding half cycles, the connections to the commutator controlling each test were reversed at regular intervals, *e.g.*, the one-second commutator was reversed through the 10-minute commutator and the one-hour one by a switch every 24 hours. In calculating the theoretical amount of corrosion, the corrosion products of both iron and lead were taken to be divalent and the quantity corroded per ampere-hour is then 1.04 grams for iron and 3.86 grams for lead.

Accuracy of Results

The accuracy which can be obtained in corrosion experiments of this kind is limited by a number of factors; first, the consistency of the corrosion action itself, which it has been found may vary within wide limits under apparently similar conditions; and second, the limits of measurement. The electrical measurements are correct to about one per cent while the time measurements are not in error more than a half per cent. The error due to weighing of single specimens was small, since it was carried to the fourth or fifth place, but in some cases the losses were small and this difference was correct to only the second or third place. This is true of practically all pilot specimens which were subjected only to natural corrosion. Therefore it is evident that the accuracy of the results is greater when the amount of corrosion is large. The combined accuracy of all measurements was much greater than the consistency to be expected in the corrosive processes.

Description of Each Run

The above description of the general condition of the tests is intended to apply to all the following data, and it will be necessary to describe each run only very briefly, deferring until later the presentation of the results.

(*a*) *Sixty-Cycle Tests.* The 60-cycle tests were run with both iron and lead specimens on the indoor tests and iron for

the outdoor tests. Both natural soil and soil with 0.5 per cent sodium carbonate added were used for the indoor tests. It will be noted from the tables presented below that in this as well as in other runs the natural corrosion losses have been rather large on the iron pilot specimens. This is due to the fact that the mill scale was not removed from these specimens before the tests were started and that the cleaning process removed this scale as well as the oxide that was formed during the test. This rather obscures the comparative effect of natural soil and sodium carbonate, but it is still evident as in the earlier tests that the natural corrosion loss of iron is greater in natural soil while the electrolytic corrosion is greater in the chemical soil. In fact in almost every instance the natural loss was greater than the electrolytic loss in the natural soil, and in five of the twelve specimens also in the chemical soil. With the three large specimens used in the outdoor tests the natural loss was considerably less than the electrolytic loss, and the coefficient of corrosion is only slightly less than one per cent.

(*b*) *Fifteen-Cycle Tests.* The 15-cycle tests were run with lead and iron in soil only, these cells being in series with about 310 volts, giving about 25 volts per cell. In every case except four iron electrodes the electrolytic losses were all greater than the natural corrosion in the same cells.

(*c*) *One-Second Period.* Iron and lead specimens in both normal soil and soil with sodium carbonate were used in the tests with one-second period, the cells being divided into four groups of three each in series. In two cases the iron electrodes lost more than the pilot specimens but on the average the losses were greater than in the preceding tests. Iron specimens were placed in outdoor soil for these tests, and in this instance the natural corrosion is unusually high because the specimens were left in the ground without current for a considerable time.

(*d*) *Six-Second Period.* Normal soil alone was used in these tests, there being three groups of cells and four cells in each group. Approximately 12.5 volts existed across each cell in order to maintain the current at about 30 milliamperes or 0.5 milliamperes per sq. cm.

(*e*) *One-Minute Period.* In the one minute reversals iron and lead electrodes were used in natural soil connected in three groups of four cells each. Approximately nine volts were maintained across the cells containing the iron electrodes and 14 volts on the lead electrodes. In case of the iron elec-

trodes there was a consistently greater loss on the odd electrode than on the even; the reason for which is not altogether evident since no such consistency exists on the lead specimens; and as the two sets were in series, it is therefore not due to unbalanced or unequal half cycles.

(*f*) *Ten-Minute Period.* Both iron and lead specimens in natural soil and soil containing sodium carbonate were used in the ten-minute period tests. The cells were divided into four groups of six each. It will be noted that the corrosion of iron in natural soil is here greater than in the chemical soil and the reverse is the case with the lead specimens.

(*g*) *One-Hour Period.* Only natural soil was used in the one-hour reversals, about 15 volts being impressed on each pair of electrodes.

(*h*) *Forty-Eight-Hour Period.* Natural soil alone was used in the daily reversals (48-hour period) with iron and lead electrodes, the entire set being in series on 240 volts. The iron specimens had a voltage of about 15 volts on each pair and the lead electrodes about 13 volts. In the case of the iron specimens the odd and even specimens, or those anode first or anode last in the test show no great or consistent difference as noted in the preliminary tests, and the lead specimens show an opposite effect from that noted at that time, that is, the electrodes which were anode during the first half-cycle have lost more than those which were cathode initially.

(*i*) *Weekly Reversals.* Both natural soil and soil containing sodium carbonate were used in the weekly reversals (2-week period) and the entire set was connected in series on 240 volts. The voltage across the iron specimen cells in the natural soil was about 15 volts per cell and about 9 volts in the chemical soil. With the lead electrodes the average voltage was less than 12 across each cell in the natural soil and less than 4 in the chemical soil.

(*j*) *Direct-Current Tests.* The d-c. tests were carried on with iron and lead specimens both indoors and outdoors and in the indoor tests with sodium carbonate in the soil as well as natural soil. The indoor cells were connected in four groups of six each with 230 volts impressed on them. The ampere-hours varied in the different groups from eight to twelve. With the iron specimens the anode losses are large, the coefficient of corrosion being approximate unity, while the cathode specimens lost less than the pilot specimens, evidently because of

the protective effect of the current. In the lead specimens, however, the anode losses are far below what might be theoretically expected, while the cathodes lost less in the natural soil than the pilot specimens but more in the soil containing sodium carbonate. This is due not so much to an increased electrolytic loss in the chemical soil, but to a greatly decreased natural loss. Since the loss in the lead specimens was so much less than might be expected another set was run under practically the same conditions but with the current maintained more closely at 0.5 milliampere per sq. cm. These results, however, corroborate the work previously done. The outdoor tests were conducted on both lead and iron with the large plates mentioned above. The protective effect of the current is noted again on the iron specimens. In the lead specimens twelve anodes were used, the lead in this case being sections of lead sheath cable, six of which contained about one per cent antimony while the other six contained only traces of tin and antimony. Two pilot specimens of each composition were used. These tests further corroborated the results of the indoor tests in that the coefficient of corrosion of lead with direct current was low.

Discussion of Results

Tables containing the summary of the results of the above mentioned tests are given below. These tables are arranged in halves with losses in grams above and the coefficient of corrosion below with the frequency or period of reversal in the first column, the average loss of six specimens in each of the three succeeding columns (the first being the odd numbered electrodes and the second the even numbered electrodes and the third the pilot specimens.) From these are calculated the electrolytic loss of odd or even electrodes shown in the fifth and sixth columns, and the seventh column contains the average electrolytic loss of all electrodes. Below the frequency is repeated and the next column contains the average quantity of electricity in ampere hours flowing through the specimens. Following this are four columns giving the coefficient of corrosion. The coefficients of corrosion of the odd electrodes and even electrodes are first given, then the coefficient of corrosion based on one-half the current or that while each electrode was positive, and last, that based on the average loss and the total current

through the cells. Since it is difficult to draw any conclusions from the electrode losses shown without also considering the ampere-hours, the coefficients of corrosion will give us the best

TABLE V

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—I.

Variable—Frequency of Reversal.

Indoor Tests
Iron Electrodes
Soil Electrolyte.

Period	Total loss: Odd electrodes	Total loss: Even electrodes	Total loss: Pilot	Electrolytic loss: Odd electrodes	Electrolytic loss: Even electrodes	Electrolytic loss: Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle........	1.480	1.289	1.645	−0.165	−0.356	−0.261
15 cycle........	1.036	0.862	0.834	+0.202	+0.028	+0.115
1 sec...........	1.064	1.190	0.640	0.424	0.550	0.488
6 sec...........	0.960	1.046	0.566	0.394	0.480	0.437
1 min.........	2.024	2.077	1.203	0.821	0.874	0.848
5 min.........	1.907	1.398	0.748	1.159	0.650	0.904
10 min.........	2.522	2.252	0.901	1.621	1.351	1.486
1 hour..........	3.134	2.941	1.165	1.969	1.776	1.872
2 days..........	5.490	5.124	1.130	4.360	3.994	4.177
2 weeks.........	8.349	9.680	1.387	6.962	8.293	7.627
D. C...........	9.697	0.139	1.023	8.674		8.674

Period	Current discharge ampere-hrs.	Coefficient of corrosion: Odd electrodes	Coefficient of corrosion: Even electrodes	Coefficient of corrosion: Average ½ current	Coefficient of corrosion: Average total current
60 cycle.........	16.05	−0.0198	−0.043	−0.031	−0.0156
15 cycle.........	13.32	+0.0292	+0.0004	+0.016	+0.008
1 sec............	17.99	0.045	0.059	0.046	0.023
6 sec............	16.83	0.045	0.055	0.050	0.025
1 min...........	19.25	0.082	0.087	0.084	0.042
5 min..........	19.99	0.111	0.063	0.087	0.043
10 min..........	16.48	0.189	0.158	0.173	0.087
1 hour..........	18.40	0.206	0.186	0.197	0.098
2 days..........	27.22	0.308	0.282	0.295	0.148
2 weeks.........	23.17	0.58	0.69	0.633	0.316
D. C............	9.82	0.85			0.850

idea of results, and these are shown in both the tables and curves.

(*a*) *Indoor Tests. Iron in Normal Soil.* In Table V a summary of the results obtained using iron electrodes in indoor

cells containing normal soil are given. As mentioned earlier, it will be seen that the pilot specimen loss is quite large and that there is considerable variation under the different frequencies. This is evidently a real variation due to a difference in soil action because it was found that in individual cases when the pilot specimen corrosion varied considerably from the average the current-carrying electrodes would also vary in the same direction. The coefficient of corrosion only in the case of the 60-cycle tests is negative. The electrodes were numbered consecutively, an odd number and a succeeding even number being grouped in each cell. The difference in the coefficient of corrosion between the odd and even electrodes is rather large in some cases; for example, in the 5-minute specimens the coefficient is 0.111 for the odd electrodes and only 0.063 for the even and in the 15-cycle test, the per cent discrepancy is large, although the values in grams do not differ greatly. The d-c. test shows a coefficient of only 0.85 which is rather low, and this can only be explained as being probably due to the effect of the iron oxide serving as a protection rather than accelerating the corrosion. The next to the last column is simply double the one succeeding or an average of the odd and even electrode coefficients.

(*b*) *Indoor Tests. Iron Electrodes in Soil with Sodium Car bonate.* In Table VI containing the results on iron electrodes in sodium carbonate soil it will be noted that in the case of the 60-cycle run the coefficient of corrosion is positive but that the values in the other cases of reverse currents are smaller than in the natural soil. In the two-weeks test the odd-electrode loss is considerably less than the even, supporting the theory that in these longer time reversals the electrodes which are positive last suffer the greater loss. Under these conditions the d-c. loss is very nearly 100 per cent.

(*c*) *Indoor Tests. Lead Electrodes in Soil.* With lead electrodes in soil very regular results were obtained. In Table VII the loss is shown to be increasing gradually from 60 cycles to 2 weeks with only one discrepancy, the even electrode in two-day reversals being considerably smaller than on the 10-minute and 1-hour specimens. The products of corrosion seem to be increasing the effect on the pilot specimens, as it will be noted that the loss is increasing as the frequency decreases. However, the most remarkable facts concerning these tests is that the odd electrodes, those which were initially

positive in the tests, lost considerably more than the even electrodes in both the two-day and two-weeks test. The other remarkable feature is the small coefficient of corrosion exhibited in the case of the d-c. test. Since in the first set weighed the losses were so small, (only 22 per cent of the theoretical) a second run was made and a coefficient of 0.25 obtained, practically the same as before. This indicates that under the conditions of these tests and probably under most soil conditions the corrosion of lead is very considerably less than it has been formerly considered to be.

TABLE VI.
SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—II.
Variable—Frequency of Reversal.

Indoor Tests
Iron Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	1.390	1.373	1.199	+0.191	0.174	+0.182
1 sec.	0.865	1.146	0.677	0.188	0.469	0.329
10 min.	1.617	1.532	0.835	0.782	0.679	0.739
2 weeks	7.922	9.081	1.636	6.286	7.451	6.868
D. C.	10.423	0.172	0.819	9.604		9.604

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle	16.05	0.023	0.021	0.022	0.011
1 sec.	17.99	0.020	0.050	0.035	0.018
10 min.	16.48	0.091	0.081	0.086	0.043
2 weeks	23.17	0.52	0.62	0.57	0.285
D. C.	9.82	0.94			0.94

(*d*) *Indoor Tests. Lead Electrodes in Sodium Carbonate.* The losses of lead electrodes in sodium carbonate (Table VIII)

TABLE VII

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—III.

Variable—Frequency of Reversal

Indoor Tests
Lead Electrodes
Soil Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	0.325	0.328	0.124	+0.201	+0.204	0.202
15 cycle	0.342	0.332	0.133	0.209	0.199	0.204
1 sec	0.385	0.354	0.118	0.267	0.236	0.252
6 sec	0.518	0.528	0.098	0.420	0.430	0.425
1 min	2.860	2.845	0.652	2.208	2.193	2.200
5 min	3.868	3.634	0.406	3.462	3.228	3.345
10 min	3.468	3.738	0.341	3.127	3.397	3.262
1 hr	5.886	5.771	0.901	4.985	4.870	4.928
2 days	8.719	5.072	1.357	7.362	3.715	5.538
2 week	13.710	7.789	1.176	12.634	6.713	9.674
D. C.	12.319	0.327	0.937	11.382		11.382
D. C.	13.574	0.277	0.882	12.692		12.692

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle	16.05	0.0065	0.0066	0.0065	0.0033
15 cycle	13.32	0.0082	0.0077	0.0080	0.0040
1 sec	14.87	0.0093	0.0082	0.0088	0.0044
5 sec	16.83	0.0129	0.0132	0.0131	0.0065
1 min	19.25	0.059	0.059	0.059	0.030
5 min	19.99	0.089	0.085	0.086	0.043
10 min	14.95	0.108	0.118	0.112	0.056
1 hour	18.40	0.140	0.137	0.139	0.069
2 day	27.22	0.140	0.071	0.105	0.053
2 week	23.17	0.282	0.150	0.216	0.108
D. C.	13.40	0.220			0.220
D. C.	12.93	0.254			0.254

are greater than in the normal soil, the difference being especially noticeable in the longer reversals and in the d-c. tests. For example, in the weekly reversals, the loss in normal soil was 0.108 while in the sodium carbonate it was 0.172; the d-c. loss has risen from about 25 per cent to 34 per cent.

TABLE VIII.

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—IV.

Variable—Frequency of Reversal

Indoor Tests
Lead Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle	0.555	0.542	0.077	0.478	+0.465	0.471
1 sec.	0.316	0.630	0.062	0.254	0.568	0.411
10 min.	4.019	3.844	0.110	3.909	3.734	3.822
2 weeks	17.356	13.487	0.111	17.245	13.370	15.307
D. C.	17.726	0.428	0.075	17.651		17.651

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average $\frac{1}{2}$ current	Average total current
60 cycle	16.05	0.0154	0.0150	0.0152	0.0076
1 sec.	14.87	0.0088	0.0198	0.0143	0.0071
10 min.	14.95	0.135	0.129	0.132	0.066
2 weeks	23.17	0.386	0.299	0.344	0.172
D. C.	13.4	0.340			0.340

(*e*) *Outdoor Tests. Iron and Lead Electrodes in Soil.* The outdoor tests shown in Table IX are not extensive, but the cases given show reasonably good agreement with the indoor tests given above. The coefficient of corrosion at 60 cycles is slightly less than 0.01 for iron electrodes and the d-c. loss is 0.70. Considering only the d-c. tests on iron, it was noted that as the voltage necessary to maintain the current at 0.5 milli-

ampere per cm. became greater the coefficient of corrosion decreased. For example, we find a coefficient of corrosion of 0.96 for iron electrodes in sodium carbonate soil and 0.85 in normal soil on the indoor tests and only 0.70 for the outdoor tests and the potential has varied from about 10 volts on the first to 35 on the last test.

TABLE IX.

SUMMARY OF ALTERNATING-CURRENT ELECTROLYSIS TESTS—V.

Variable—Frequency of Reversal.

Outdoor Tests
Iron and Lead Electrodes
Soil and Sodium Carbonate Electrolyte.

Frequency of reversal	Total loss			Electrolytic loss		
	Odd electrodes	Even electrodes	Pilot	Odd electrodes	Even electrodes	Average
	Grams	Grams	Grams	Grams	Grams	Grams
60 cycle....	2.65	2.60	0.97	1.68	1.63	1.65 Iron
1 sec.......	9.06	7.30	5.94	3.12	1.36	2.24 Iron
D. C.......	41.96	1.73	4.61	37.35	37.35	37.35 Iron
D. C.......	871.861		6.216	865.645		865.645 Lead

Frequency of reversal	Current discharge ampere-hrs.	Coefficient of corrosion			
		Odd electrodes	Even electrodes	Average ½ current	Average total current
60 cycle.......	165.4	0.0203	0.0197	0.0192	0.0096 Iron
1 sec..........	102.	0.0589	0.0256	0.0431	0.0215 Iron
D. C..........	51.6	0.700	0.700	0.700	0.700 Iron
D. C..........	1034.	0.217	0.217	0.217	0.217 Lead

Curves

The data shown in the above tables have been plotted in curves in which the ordinates are coefficients of corrosion expressed in per cent and the abscissas are the logarithms of the number of seconds required for one complete cycle. Fig. 4 shows the data obtained with iron electrodes, these being based on the average electrode loss and the total current flowing in

any one direction through the cells. The coefficient is therefore based on the total current discharged by one electrode. It will be noted that the curve for the coefficient in natural soil is above that for soil containing sodium carbonate except the last point for direct current when the latter shows the greater loss. The values begin to rise quite rapidly at about the 10-minute cycle and reach a maximum in the d-c. test, the value for which is placed arbitrarily as far as the time is concerned. It is very interesting to note that even in the case of a cycle of two weeks duration the coefficient of corrosion is only about 0.6 and on a 2-day cycle only 0.3 of its value for direct current.

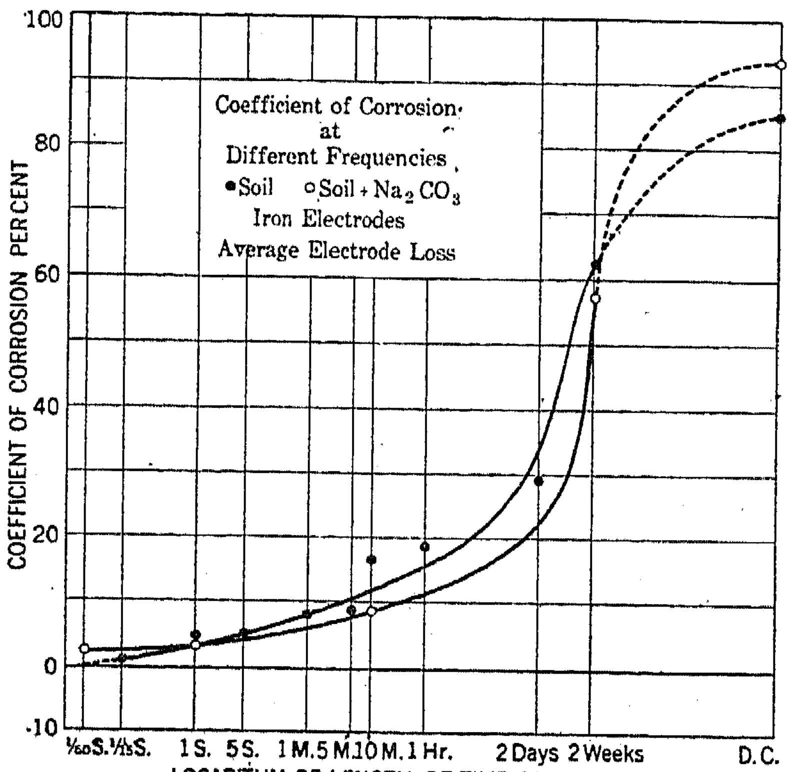


FIG. 4

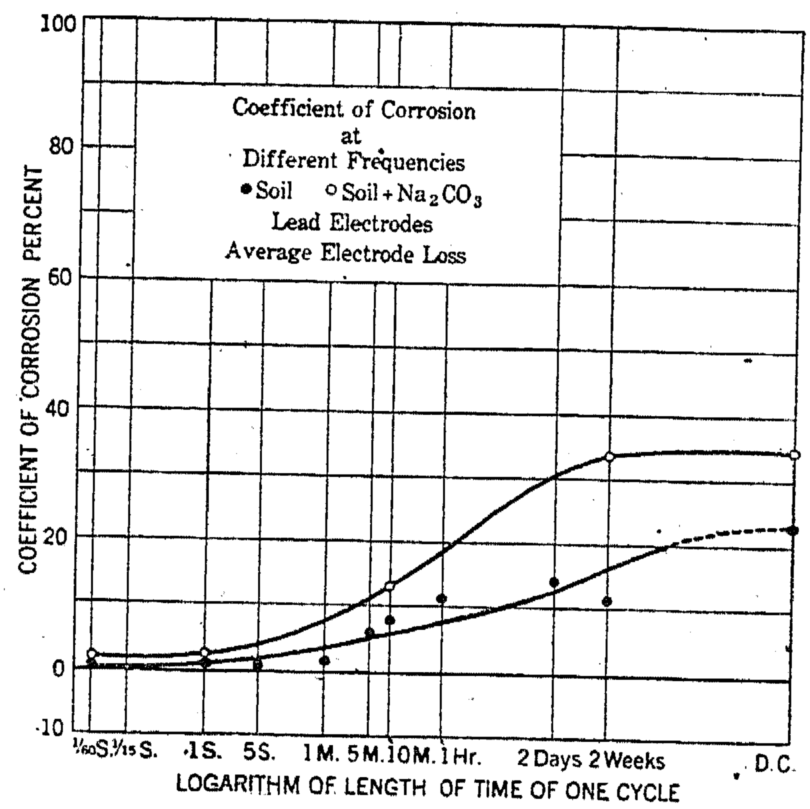


FIG. 5

Fig. 5 contains the same data on lead electrodes and here it is seen that the soil containing sodium carbonate produces a consistently higher coefficient of corrosion than the natural soil, just the reverse of the condition with iron electrodes. The tendency to rise is noticed at an earlier point or a higher frequency than with the iron, beginning with about the one-minute cycle, and at a cycle of two weeks duration the coefficient of corrosion has reached the same value as for direct current.

SUPPLEMENTARY TESTS

Since certain authors have pointed out the fact that the wave form of alternating current is affected when passing through an electrolytic cell, and since a material change in such wave form would affect the current measurements, an

oscillograph was used to determine the wave form of current passing through the cell and its relation to the potential wave impressed on it. It was found that there was no appreciable distortion of the wave shape due to the presence of the cell.

In order to determine the cycle of operation of the commutating machine exactly, the current wave was observed with the oscillograph. It is seen that on the one-second cycle, Fig. 6, the current increases slightly during about the first $\frac{1}{4}$ second and falls during the remainder of the half-cycle. In the six-second cycle, Fig. 7, this rise and fall is seen and the fall continues for a considerable part of each half cycle, but the waves appear to be so nearly flat top in both the 1-second cycle and the six-second cycle that no correction due to the variation between the average value and the effective value need be made.

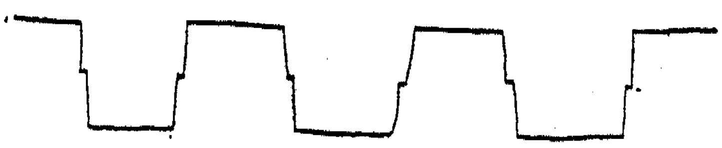


FIG. 6—WAVE SHAPE FOR SLOWLY REVERSED CURRENT—ONE-SECOND CYCLE

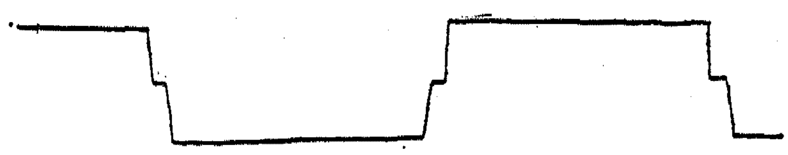


FIG. 7—WAVE SHAPE FOR SLOWLY REVERSED CURRENT—SIX-SECOND CYCLE

III. CONCLUSIONS

From the above results certain conclusions may be drawn concerning the corrosion of iron and lead electrodes under usual soil conditions when exposed to the action of periodically reversed current.

1. The corrosion of both iron and lead electrodes decreases with increasing frequency of reversal of the current.

2. The corrosion is practically negligible for both metals when the period of the cycle is not greater than about one minute.

3. With iron electrodes a limiting frequency is reached between 15 and 60 cycles per second, beyond which no appreciable corrosion occurs. No such limit was reached in the lead tests, although it may exist at a higher frequency than 60 cycles.

4. With periodically reversed currents, the addition of sodium carbonate to the soil reduces the loss in the case of iron and increases it in the case of lead.

5. The coefficient of corrosion of lead, under the soil conditions described in the report, when subjected to the action

of direct current was found to be only about 25 per cent of the theoretical value.

6. The corrosion of lead reaches practically the maximum value with a frequency of reversal lying between one day and one week.

7. The corrosion of iron does not reach a maximum value until the period of the cycle is considerably in excess of two weeks.

8. The most important conclusion to be drawn from these investigations is that in the so-called neutral zone of street railway networks where the pipes continually reverse in polarity, the damage is much less than would be expected from a consideration of the arithmetical average of the current discharged from the pipes into the earth. Where pipes are alternately positive and negative with periods not exceeding 10 or 15 minutes, the algebraic sum of the current discharged is more nearly a correct index to the total damage that will result than any other figure that can readily be obtained.

9. The reduction in corrosion due to periodically reversed currents appears to be due to the fact that the corrosive process is in a large degree reversible; so that the metal corroded during the half cycle when current is being discharged is in large measure redeposited during the succeeding half cycle when the current flows toward the metal. This redeposited metal may not be of much value mechanically, but it serves as an anode surface during the next succeeding half cycle, and thus protects the uncorroded metal beneath.

10. The extent to which the corrosive process is reversible depends upon the freedom with which the electrolyte circulates, and particularly, on the freedom of access of such substances as oxygen or carbon dioxide, which may result in secondary reactions giving rise to insoluble precipitates of the corroded metal. It is largely for this reason that the corrosion becomes greater with a longer period of the cycle since the longer the period the greater will be the effect of these secondary reactions.

DISCUSSION ON "THE INFLUENCE OF FREQUENCY OF ALTERNATING OR INFREQUENTLY-REVERSED CURRENT ON ELECTROLYTIC CORROSION" (MCCOLLUM-AHLBORN), NEW YORK, MARCH 10, 1916.

Philip Torchio: The most important results in the findings in these investigations are, first, that with ordinary frequencies of 25 to 60 cycles, the corrosion of underground structures is, practically nil. In this country some of the water companies are still objecting to having the electric lighting companies ground their neutrals to the pipes of the water companies. I think that the results of the investigation of the Bureau of Standards should dissipate any fear of trouble due to the grounding of neutrals to the water pipes.

The next important point brought out by the paper, which should dissipate another fear, is that with potentials in a certain zone changing from positive to negative, which fluctuation may occur in periods represented by the passing of a car with time intervals of possibly five or ten minutes, the corrosion would be negligible.

The next important conclusion to be drawn from the paper is rather astonishing, in so far that only in this year of 1916 a paper of this character should be presented to the railway engineers seriously proposing to ameliorate electrolysis conditions by reversing the polarity of the trolley at certain intervals, as, for instance, of one hour, or a day, or even a week, and showing that by so doing the damage by electrolysis may be reduced to one-tenth, or one-quarter of what it would be by keeping the trolley potential constant, as we are accustomed to do.

Now, this suggestion of reversing the potential of the trolley is not a new one. It cannot be ascribed to ignorance, that this method has not been tried, because as far back as 1902 a Danish engineer, Mr. Absalon Larsen, published in the *Elektrotechnische Zeitschrift* of September 1902, the results of his tests made in the Copenhagen Polytechnic Laboratory; and also a field test, both carried out on practically the same lines as those carried out by Messrs. McCollum and Ahlborn. Making allowance for the immeasurably greater details and completeness of the investigation of Messrs. McCollum and Ahlborn, and also the more complete scientific methods of procedure, it is astonishing that the results obtained in Copenhagen fifteen years ago are in their broad general lines confirmed by the results of the work in the Bureau of Standards.

In Mr. Larsen's paper he states briefly, that the results are as follows: That with one reversal per day the electrolytic action can be reduced to one-quarter, and by one reversal per hour it can be reduced to one-thirtieth of its normal value. From the tables given in to-night's paper we see that the results with one reversal every two days would be in the order of one-quarter,

and one reversal every hour would be in the order of one-tenth, and it is, therefore, broadly speaking, astonishing that in fifteen years no use whatsoever has been made of the suggestion presented by Larsen.

Two years ago the Joint National Committee on Electrolysis reported on European practise. I made a survey throughout certain of the European countries, and before starting from America I consulted with Dr. Rosa on what line of investigation I should follow, and on his suggestion I had prepared a list of questions to ask every gentleman I interviewed. As a result of all of the interviews I had in England, France, Germany and Italy, I found that this suggestion of the reversal of potential was practically never used. The only places where the potential of the trolley has been reversed were in St. Gall and Nürnberg, but that was done only once, to try to remedy electrolytic conditions. In all other cases practically no application has been made of this suggestion which appears to promise great benefit in many bad electrolysis situations.

Now, I would like to hear from railway engineers why this is so, why this suggestion, which undoubtedly has been known for fifteen years, has never been applied, and then what are the objections to applying it.

Alexander Maxwell: I think the authors of this paper should be congratulated for their investigation of this very practical phase of the general subject of corrosion of underground structures by stray currents, particularly with regard to that part of the investigation which deals with reversing continuous currents, as distinguished from alternating currents of the ordinary frequencies. It is too often assumed that serious corrosion occurs only where the affected structures are close to the rails and positive in potential to them, whereas corrosion is frequently found in the so-called "neutral zones" as well as in locations remote from railway structures, in the latter case corrosion being due to exchange of current between different piping or cable systems, very often associated with reversals of direction.

In one respect, however, I desire to offer a criticism which repeats a similar comment of mine in connection with an earlier paper of one of the authors, namely, that the current densities employed are much higher than those encountered in practise. To be sure, the authors have offered a good reason for the current density employed, but it seems especially unfortunate that lower densities were not investigated on account of the uncertainty which remains regarding the precise nature of the corrosion where low corrosion coefficients were found.

Two examples taken at random illustrate the magnitude of the apparent current densities which may be met in practise, associated with actual corrosion. In one case current having a 24-hour average value of 3.4 amperes, flowed from a 20-inch cast iron gas main between two test stations, 150 feet apart. This works out to 0.0046 milliampere per sq. cm., average, over

the whole surface. Therefore, only about 1/100 of the whole surface would be conducting to attain the current density used in the experiments described in the paper.

In another case, serious damage was done to cable sheaths by the loss of one ampere in a single section between manholes. Since the cable was of large diameter, it may be assumed that the lowest 1-inch of circumference was in contact with moisture and soil in the conduit, the minimum distance between manholes was about 250 feet. Under these conditions, the contact area would be 19,350 sq. cm., and the average current density would be 0.052 milliamperes per sq. cm., or roughly, 1/10 of the value used in the paper.

I do not mean to say that densities as low as these average densities should necessarily be employed for experimentation, but that something approximating them should be employed in view of the admitted influence of secondary effects which greatly increase the corrosion coefficients at low densities, and which might strongly influence an investigation like the present one. Moreover, it should be borne in mind that the average current densities referred to above may still be directly compared with the densities used by the authors, since theirs are also average densities.

A. F. Ganz: Several papers have been published describing the results of experiments with alternating currents of commercial frequencies in producing electrolysis of iron in soils and in solutions. The results of these experiments have generally shown that with alternating current some corrosion results, but that this is only of the order of one per cent of that calculated by Faraday's law from the quantity of electricity discharged from the anode. The present authors have found substantially the same results with alternating currents of frequencies of 15 and 60 cycles per second. The authors have also included tests using direct current which was reversed at relatively long intervals, the periods varying from one second to two weeks. They have found that even with the longest period of reversal, the corrosion produced is less than that computed by Faraday's law from the total quantity of electricity leaving the anode, and that the corrosion of both iron and lead electrodes decreases with increasing frequency.

The authors have used a current density of approximately 0.5 milliampere per sq. cm. for the iron and also for the lead samples, which is approximately 0.46 ampere per sq. ft. This current density is probably over 10 times as great as is generally found in practise in the case of pipe and cable sheaths affected by stray currents. The authors state that this current density was used because in a previous investigation on the corrosion of iron in street soils, it had been found that with current densities no greater than these, coefficients of corrosion of practically unity were obtained with direct current. I would like to ask the authors whether in the case of lead, similar tests

were made, and if so, whether with much smaller current densities, a coefficient of corrosion as low as 25 per cent was also found. It is well known that as the density of current flowing from a corrodible anode to an electrolyte is increased, a point is reached where, in addition to the metal going into solution, gases are formed so that only part of the electricity is effective in dissolving the anode, and the other part produces gas. If tests with lower current densities on lead samples have not been made, it seems to me that this should be done before the conclusion can be accepted that with lead as an anode the corrosion is only 25 per cent of that calculated by Faraday's law.

The present tests were made with only one kind of soil. It is entirely possible also that with soils containing other constituents than the soil used, a higher coefficient of corrosion may be found for lead.

Assuming, however, that the corrosion from electrolysis with lead anodes is under practical conditions only 25 per cent of that calculated by Faraday's law, it seems to me that this makes alternating or infrequently reversed currents much less advantageous in the case of lead than is indicated by the coefficients of corrosion given for these currents in the paper. To make clear what I mean, I find in Table VIII that with a frequency of reversal of 10 minutes, the average coefficient of corrosion is given as 0.132. This figure is obtained by dividing the actual loss from electrolysis by the loss calculated by Faraday's law. If, however, with direct current the coefficient of corrosion is 25 per cent instead of 100 per cent, the beneficial effect of a frequency of reversal of 10 minutes is represented by four times 0.132 or by 0.528, and not by 0.132. This means practically that if with direct current a certain amount of corrosion is produced, a reversing current having a frequency of 10 minutes will cause a little more than half as much corrosion as the direct current. As it is well known that lead cable sheaths in practise are very rapidly destroyed by localized pitting where they are at all times positive to earth, and even where a relatively small current flows from the cable sheaths, it is evident that much less improvement is to be expected from alternating or from infrequently reversed currents in the case of lead cable sheaths than is indicated by the coefficients of corrosion given in the paper.

The authors state that the reduction in electrolytic corrosion from alternating or infrequently reversed currents appears to be due to the fact that the corrosive action is in a large degree reversible. While the results of the tests indicate that this may be the action, I do not believe that they are sufficiently conclusive to prove this theory, and it would be very desirable to have this phase of the subject discussed theoretically from an electrochemical standpoint. This is to my mind extremely important because it may serve to answer the question as to whether the low coefficients of corrosion found in the present tests may also be expected with the widely varying conditions of the electrolyte found in practise.

On the basis of the very low coefficients of corrosion found where the reversal is one minute or less, the authors draw the conclusion that where underground pipes or cable sheaths reverse more or less continually in polarity, the algebraic average of the current or potential is more nearly a correct index of the total damage that would result from electrolysis than any other figure that can be obtained. All of the tests described in the paper were however made with reversed currents whose algebraic average is zero. In order to prove the validity of the algebraic average for judging danger from electrolysis, it seems to me that it would be desirable to make experiments in which the algebraic average is other than zero, and particularly with reversed currents in which the periods for the positive lobes are made substantially longer than the periods for the negative lobes.

From a practical standpoint it seems to me that it would also be very misleading to give only the algebraic average of the potential or current, where these quantities continually reverse. This will readily be seen from the fact that large currents may reverse in underground cable sheaths or pipes, and yet the algebraic averages may be zero, so that if the results are expressed only as algebraic averages, an entirely false impression is created. There are other dangers from stray currents flowing on underground pipes and cable sheaths besides electrolysis, as for example fire hazards from sparks or arcing where currents pass through buildings on service pipes or cables. These dangers are not in any sense measured by the algebraic average of the currents.

I want to say in conclusion that if the low coefficients of corrosion found by the present authors, even with very slowly reversed currents, are substantiated for soils generally and for the low current densities usually met in practise, methods of electrolysis mitigation which result in large areas of reversing polarities of the underground structures, such as insulated return feeder systems and three-wire systems, assure a much greater degree of protection from destruction by electrolysis of these structures and particularly of iron structures, than has previously been expected. The work described by the present authors has therefore wide practical application and it is fortunate that we now have the results of this work available.

J. L. R. Hayden: I agree with the author's conclusions except in some minor features.

I do not believe that there is a limiting frequency beyond which no appreciable corrosion occurs. While at 25 cycles, the corrosion is already less than 1 per cent in most cases, there is still a distinct decrease at 60 cycles, and traces of electrolytic action seem to remain even at very much higher frequencies. At the low current densities used in the experiments the chemical corrosion is comparable with the electrolytic, and as the chemical corrosion is very variable, a serious source of error results at these frequencies, which in my opinion is the cause of the apparently negative corrosion at 60 cycles, in Table V.

I agree with the experience that alkaline solutions chemically protect iron, but attack lead.

The low coefficient of corrosion of lead may be apparent only, and due the assumption of lead as bivalent. As in the lead storage battery the anodic action proceeds to PbO_2, it appears probable that with unidirectional current of long duration, Pb shows valency 4. This would double all the corrosion coefficients of lead. At higher frequencies, lead probably is bivalent, and this would account for the different slopes of the lead and the iron curves.

The observer's results seem to agree with my experience that iron is more erratic than lead. This I explained by the ease, with which iron can assume the passive (probably trivalent) state. As time, current density (even momentary), previous history and nature of electrolyte (nitrates favorable, chlorides unfavorable for passivity) and surface condition (presence of scale) have a material influence on passivity,* during half cycles of long duration the iron electrodes may change from active to passive and inversely. As active iron appears to be bivalent, passive iron trivalent, the previous hydrogen electrode, when changing to anode by reversal of current, would tend to start active. This may account for some of the differences between the odd and even electrodes.

As nitrates and ammonia are frequent constituents of soil, and nitrates have a strong passivating effect, it would have been interesting to make some experiments with soil containing ammonium nitrate for instance.

Also, the action of higher current densities would be of interest, especially with lead electrodes. Lead cables laid in ducts are usually fairly well insulated except locally, where moisture may have penetrated etc. With such lead cables the current flow may be localized, and then higher densities result.

S. M. Kintner: The practical value of the information sought by the author, in so far as it relates to engineering practise in most instances at least, is the assistance it will give in forecasting what will happen to a pipe or lead covered cable buried in the ground and subjected to such electrolytic actions. A pipe, or cable, under such conditions fails by a small hole, or at least only a small hole is sufficient to cause serious trouble very shortly. This being the case it is of rather academic interest to know whether the pipe as a whole has lost one per cent in weight, or even ten per cent.

Even if we knew, quite accurately how the loss varied with current density etc., we could make no practical use of it, in an application such as that assumed, for the very evident reason that we have no control over the current distribution as it goes to or from such a buried pipe. What we are interested in, however, is the order of the loss that may be expected, compared to

* "Electrolytic Corrosion of Iron by Direct Current", *Journal of Franklin Institute*, October 1911.

that due to d-c. electrolysis, or to ordinary corrosion under like conditions of soil.

The paper contains some very interesting results on the effects of infrequent reversals of direct current. These results are of considerable practical value, if applied with proper discretion.

In a series of tests on a-c. electrolysis made by me in 1904-5 and reported in part in the *Electric Journal* of 1905, attempts were made to secure accurate data. Both iron and lead plates, weighed accurately before and after subjecting them to a-c. electrolytic action, were used.

The plates of iron in some test boxes, and lead in others, were arranged so as to form the two ends of small boxes, of which the other sides were of wood. Some 20 or 30 of these were used in various combinations of frequencies, of electrolytes, of current densities etc. It did not take long, however, to show that the current densities varied greatly, that the "gain" plates of the direct current cells lost as much, or more than those plates subjected to the simple corrosion or to the a-c. electrolytic action and that the cleaning for weighing was apt to produce greater losses than the losses it was expected to detect.

The d-c. "loss" plates would be eaten through at places slightly below the surface, while at other places down deeper in the solution the action was comparatively slight. This was quite conclusive proof that the current densities were not uniform over the whole plate surface. The mounting employed was expected to eliminate the greater density at the edges of the plates and thus secure a closer approximation to uniformity of current density.

It is to be noted that in the present paper no such precautions were taken and so it is reasonable to expect even a greater variation in current density than in the tests made by me in 1904.

After concluding a number of the plate tests, all laboratory tests, and reaching the decision that no data of a greater degree of refinement were obtainable or even if obtainable, could be applied practically, it was decided to check the general observations by tests approximating as nearly as possible, the actual operating conditions. Consequently a number of pipes of about four feet length and three inches in diameter, were buried after being carefully weighed, marked and having their ends sealed with an asphalt gum. These pipes, both commercial wrought pipe and lead cable, were buried in three different localities separated some 25 miles from each other. These test pipes were arranged in groups in each of the three localities and in this way the effects of frequency, current density, (insofar as total current per pipe would indicate it) direct current and simple corrosion were observed. Pipes were buried at different depths varying from two to six feet. There was a sufficient number of pipes in each combination to permit the removal of some after various periods of action. They were all removed at the end of one year.

Attempts at weighing and checking against the original weights, proved of no value whatever.

A careful study of them did show that effects of the a-c. electrolysis, both 25 and 60 cycle, was just about the same as that shown by pipes subjected to corrosion only.

Fortunately the character of soil, in the three places in which they were buried, differed very materially.

The effects on the pipes of the alternating currents followed quite closely, in each of the three places, that produced by corrosion only.

The serious effects noted were pits, some quite deep, while the pipe immediately adjacent was in good condition with no signs of pit marks. The pits were no different on the pipes subjected to the alternating current than those where corrosion only had caused the action. This indicates either a variation in the pipe, or a variation in the soil in which it is buried, which sets up a very strong local activity.

Carl Hering: The results given in the paper are of interest and of value, especially as some of them are different from what was probably supposed to be the case, while others confirm by experiment what heretofore was a mere belief. One of the most valuable results is that in what are called the neutral districts in underground electrolytic corrosion problems, the periodic reversals of current practically neutralize each other; also that corrosion from underground alternating currents of the usual frequencies, is not a serious menace; there were good reasons for believing that for lead covered cables at least, the corrosion due to underground alternating current might be serious.

Asa P. Way: This paper suggests an attempt made about six years ago for the mitigation of electrolysis in two instances, one of which was very familiar to me. In this method a specially designed transformer was used through the low voltage side of which passed the return current of one or more pipe drainage feeders connected to taps of different potential. The primary was excited through resistance by an intermittent current from a 550-volt d-c. source. The idea was to set up a relatively low frequency reversing potential between pipes and rails. However, financial as well as mechanical difficulties, I believe, prevented the development of the installations, although there appeared to be merit in the scheme.

However I have had in mind for some time to use the principles set forth in this paper in connection with the insulated negative feeder system but particularly with such an installation put in operation about two months ago. In this particular installation two of the feeders connect to a track about 4000 feet apart where tracks are consistently negative to water pipes although conditions are not dangerous, due principally to some poor track bonding in the neighborhood. My idea is to place in series with each of these feeders a definite amount of resistance alternately to be short circuited by automatically operated

contactors. The resistances would be so designed that when one is short circuited and the other is in series with the other feeder and vice versa the potential between pipes and rails at the ends of the feeders would alternately reverse. It might be found that one resistance in series with the return current of both feeders could be alternately short circuited and left in series which would probably increase the area subject to reverse current flow between pipes and rails. The contactors could be operated by a relay controlled by a sign flasher or any other convenient method. I would like to know if the authors of this paper think that would be effective.

C. B. Martin: The tests described in this paper were made in soil. This condition is the usual one that must be considered in connection with standard trolley roads, but in connection with electrified heavy traction roads the effect of reversing currents upon steel imbedded in concrete becomes of importance.

For the last twenty-five months we have had under test, units made of one inch steel rods, six inches long, surrounded by two inches of concrete placed in water baths in metal pails. In some of these units the current has flowed in the direction to produce electrolysis of the rod, and in others the same current was reversed at the rate of 0.8 cycles per minute. The resistance of the d-c. units increased steadily, while that of the reversing units hardly at all.

How well the steel embedded in concrete of the d-c. unit automatically protected itself will be seen by the reduction of the current with the same impressed potential. At the start the current flow was 0.08 amperes; in ten days 0.04; in thirty-four days 0.02; in three hundred and twenty-eight days 0.01, and in seven hundred and sixty days 0.005. The efficiency of corrosion for the whole period was 28.4 per cent.

The average current flowing was 0.053 milliamperes per sq. cm. of the surface of the rod, which is about one-tenth of that required to produce the maximum corrosion of iron. This low density is, however, very much above that encountered upon the steel structures in which we are most interested.

An examination of the reversed current electrode showed that it was but slightly affected. Only 0.588 of a gram of metal had been removed, and the efficiency of corrosion was only 0.95 of one per cent of the positive current flowing.

The results of our reversing tests on steel in concrete, therefore agree very closely with the results reported in the paper on reversing tests in soil. In both cases the resulting electrolysis is practically negligible.

Another test which we made in 1912 is interesting. An electrolysis test sample similar to those described above which had been under test for three weeks with a positive potential on the electrode increasing from 12 volts to 52 volts, as the internal resistance of the sample increased, was subjected to a current reversing every minute, and the varying resistance of the circuit recorded.

See Fig. 1. It will be seen that very promptly upon the reversal of the current there was a surprising drop in the resistance, which was partially restored upon again making the electrode positive. Under repeated reversals the resistance of the sample steadily decreased with every indication that a stable condition had been reached. Finally the electrode was again subject to a steady positive potential and the resistance increased to an approximation of its original value. Naturally the question arises what caused the resistance to increase and decrease in this manner? Was the action due to gases or the expulsion and return of the electrolyte? At any rate the test shows that the resistance of the electrolytic circuit of steel encased in concrete is built up by making the steel positive, and broken down by making it negative.

Electrolysis engineers working to protect underground struc-

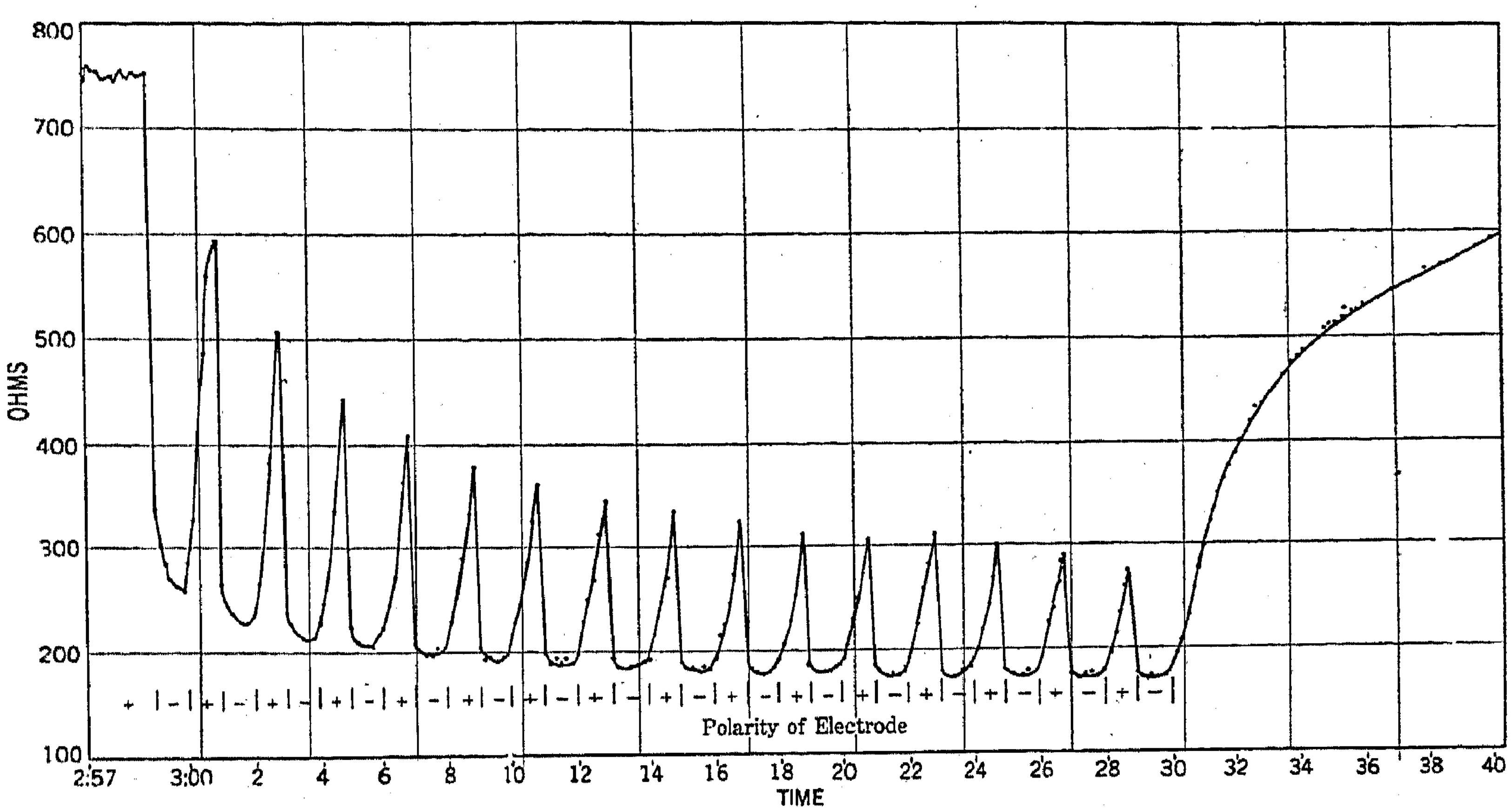


FIG. 1

tures from electrolysis have constantly before them the statement that one d-c. ampere flowing steadily for a year will disintegrate twenty pounds of iron, or seventy-five pounds of lead under favorable conditions. Should such rates of deterioration be realized in practise many important structures would be in need of extended repairs, and the expenditure of very large sums in protective measures would be justified.

When, however, foundations, especially steel foundations encased in concrete have been uncovered and found to be but slightly affected, although subjected to a potential favoring electrolysis for years, the question naturally arises whether there are not circumstances which in practise largely reduce these large estimates of electrolysis damage.

The paper of the evening demonstrates the existence of at least one very important condition that materially retards electrolysis in many localities.

An important conclusion that should be drawn from the paper is that in an electrolysis survey, readings should be taken for twenty-four hours, preferably by means of recording instruments so that the full cycle of a day's operations will be included and all current reversals recorded.

We are particularly interested in the statement that the loss of lead in soil under d-c. flow is about 25 per cent of the theoretical loss. We trust that this important phenomena will be more fully investigated and explained. Tests which we have made upon electrolysis samples of steel surrounded by two inches of concrete indicate that the efficiency of corrosion is not over 30 per cent. Some of these tests have extended over long periods.

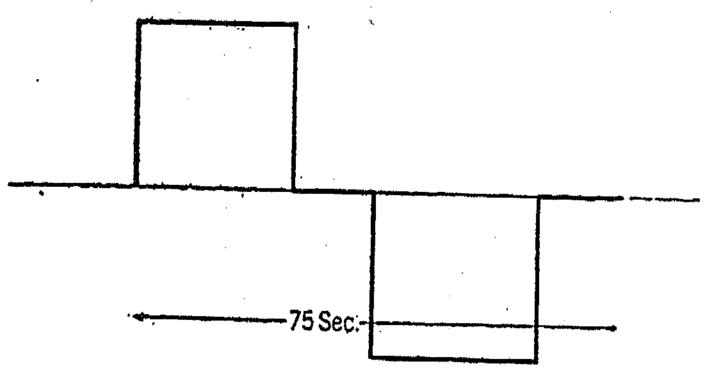


FIG. 2

Referring to conclusion (2) of the paper that "the corrosion is practically negligible for both metals when the period of the cycle is not greater than about one minute," we have understood that when electrolysis is taking place under ordinary conditions that water molecules are broken up and the gases collect at the anode and cathode surfaces. Upon reversal of current, is it not possible that these gases, especially the hydrogen gases, in some way interfere with the prompt starting of electrolysis? May it not take about a minute to dissipate these gases?

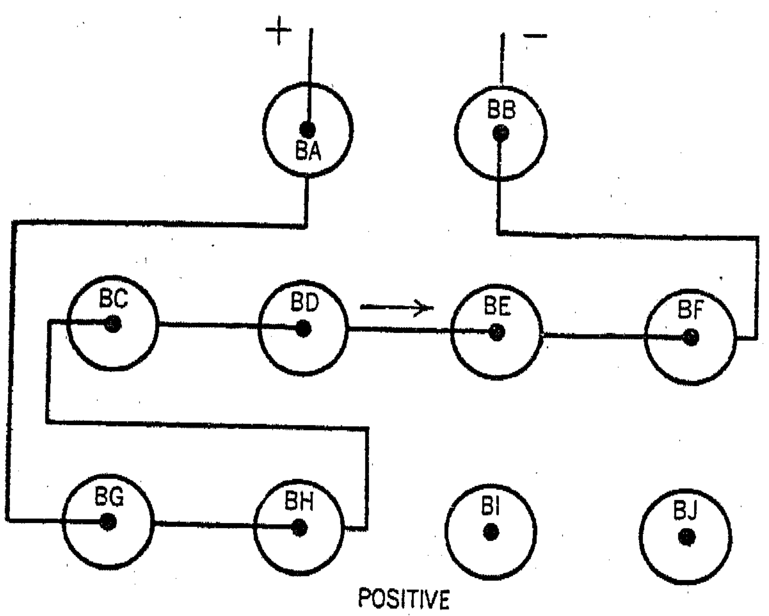


FIG. 3

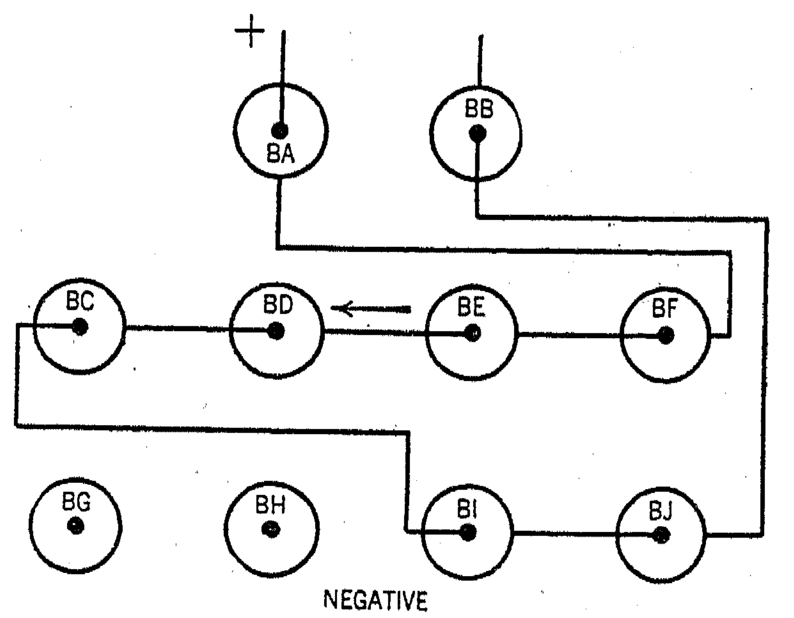
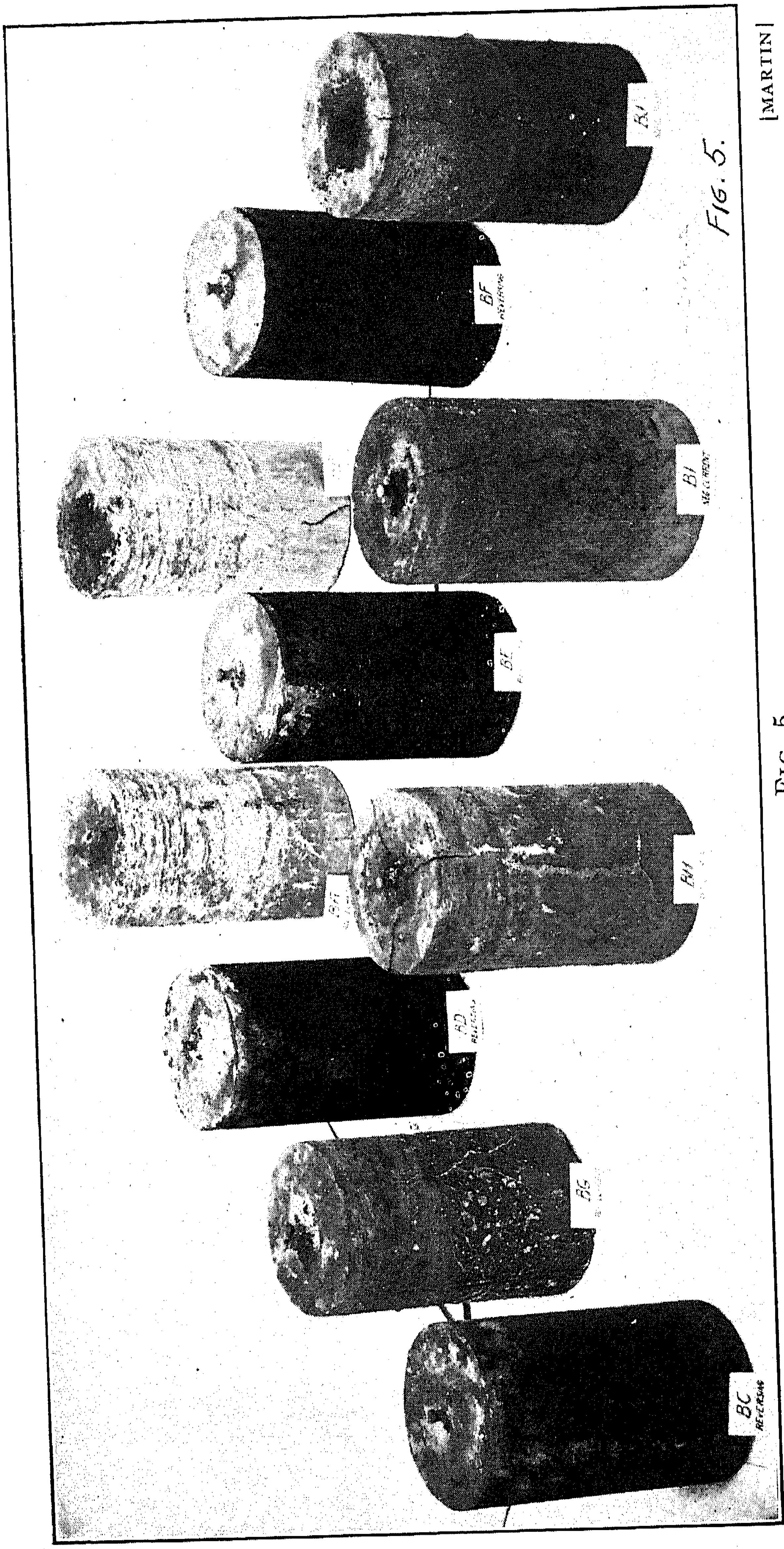


FIG. 4

In the twenty-five months' test referred to above, there was a period without flow of current between each reversal amounting to about one-third of the time. The shape of the current curve is shown in Fig. 2.

In addition to the four samples subjected to reversing test there were six others that were connected in circuit as shown in Fig. 3 and Fig. 4.

In Fig. 5 is shown all the samples at the end of the twenty-five months, each sample being lettered corresponding to its position in Fig. 3 and Fig. 4.



[MARTIN]

FIG. 5

Thomas M. Roberts: My remarks will be a brief comment on conclusion No. 8.

Fig. 6 represents a rise of potential in a pipe line above a given zero, and a simultaneous drop of potential in the rails with the going and coming of cars. It is to be noted that the change of potential of the conductors in the earth is greater as the distance between the bond points increases. This probably is known to many railway engineers, but it is not so well known to many who install underground systems of piping which may become bonded with electrical conductors. I simply call attention to the fact that in an active zone a well bonded system of pipes and conductors suffers less from electrolysis than a poorly bonded system. This we know irrespective of whether the electrolytic effects are caused by an arithmetical average or by the algebraic sum of the currents. The effect is what it is, irrespective of the name given to the cause. The name is a small matter; the method of installation is the important thing.

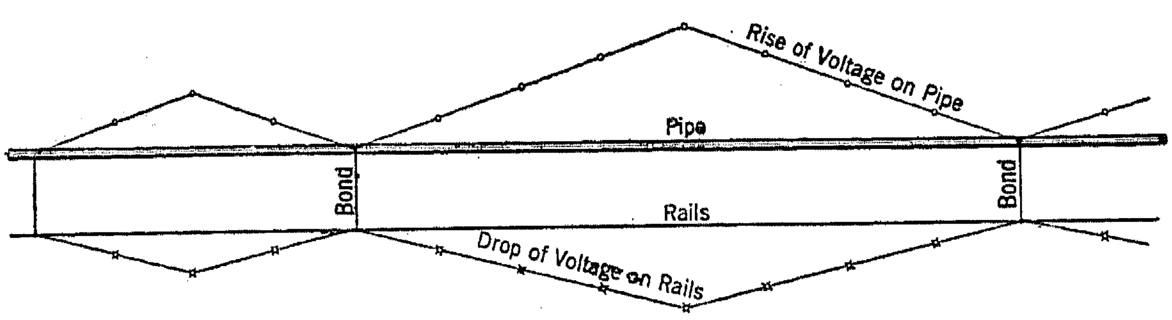


FIG. 6—DIAGRAM SHOWING INCREASE OF POTENTIAL DIFFERENCE BETWEEN PIPE AND RAILS WITH INCREASE OF DISTANCE BETWEEN BONDED POINTS

L. W. Chubb: We carried out about a year ago a test with slow reversal currents. In the control of large induction motors it has become quite common to feed the secondary through a water rheostat, as it is called. The frequency of alternation starts at 25 or 60 cycles, and as the motor speeds up the frequency drops to the slip frequency which is less than one cycle per second.

There has been some corrosion trouble with the metal electrodes in different parts of the country and very careful tests were made to find the effects of purity of water. These tests were carried out not in as much detail as they might have been, but they showed conclusively that the water, although reasonably pure, as pure as the moisture of the soil, has a great bearing on the result. Tests were made from 60 cycles down to 0.1 of a cycle per second, the low cycles being obtained by feeding from the secondary of the induction motor, with a constant slip, and by reversing direct-current with a rheostat which cut in and out the resistance, so that the wave shape approximated a sine wave. The specific results are covered in Mr. Spooner's discussion.

Sodium carbonate is used in water rheostats. It is used because it causes little corrosion. For this reason I believe it was not a very representative chemical to add to the soil employed in the test described in the paper. I think it is

to be regretted that the authors cleaned their samples as they did, and did not take off the scale before the test was made.

Prof. Ganz said, that the usual current reversals do not have an average value of zero. I might say that it is possible that the average value of the test current was not zero in these tests, which may account for the great discrepancy between odd and even plates, and also increase the results. If the ampere-hours in each direction are equal, we should expect a very much lower corrosion than if there is, say, one per cent increase in one direction over the other. In our tests we met this trouble, and had to make a good many of the tests over again. We used ampere-hour meters to integrate the current first in one direction and then in another.

Thomas Spooner: Almost a year ago we made some tests on the effect of frequency of alternating current on the rate of corrosion of various metals and alloys in solutions of 2 per cent sodium carbonate and in sea water. The tests were largely qualitative, but they may add something of interest to this subject.

The investigation was made on plates of various materials immersed in electrolytes contained in beakers. There was no stirring beyond that produced by the electrolytic action. Each plate had an immersed area (one side) of about 2.7 sq. in. (17.4 sq. cm.) and the average current varied from 5 amperes to 1 ampere, the higher the values being used only on a few preliminary tests. The average current for most of the tests was about 2 amperes. The tests were made with various frequencies from 25 to 0.1 cycles per second. The results are expressed in loss of weight in grams per ampere-hour. Some of the results obtained are as follows:

TABLE I.—ELECTROLYTE—2 PER CENT SODIUM CARBONATE
LOSS IN GRAMS PER AMPERE HOUR

Frequency cycles per sec.	*Ingot iron	Monel metal	Nickel chromium alloy	Current supply
0.1	0.0175	0.0008	0.0021	Reversing switch
0.1	0.0155	0.0014	0.0030	Revolving rheostat
0.2	0.0055	0.00077	0.0030	"
0.5	0.0021	0.00084	0.0017	"
1.0	0.0011	0.00056	0.00078	A-c. generator
5.0	0.00015	0.00011	0.0022	"
25.0	0.000012			Shop supply

TABLE II. ELECTROLYTE—SEA WATER.

0.1	Badly corroded in 3½ hrs.	Badly corroded 3½ hrs.	Entirely eaten away in 1½ hrs.	Revolving rheostat
1.0	0.0041	0.0111	0.0498	A-c. gen.
5.0	0.0022	0.0098	0.0401	"

*Ingot iron was tested in sodium carbonate solution with d-c. It was badly corroded at end of 9½ hours.

A few tests were made on a 5 per cent nickel steel alloy (rolled), a 5 per cent nickel steel alloy (cast), and boiler plate. The first two corroded rapidly, while the last at frequencies of 0.5, 1.0 and 5.0 and a 2 per cent sodium carbonate solution gave the same results as the ingot iron within the limits of accuracy of the test.

The first 0.1 cycle tests were made with a motor driven reversing switch which was open about the same length of time it was closed. The revolving rheostat tests were made with an apparatus as shown in Fig. 7. The operation of the device is obvious from the figure. It gave a wave like that shown in Fig. 8.

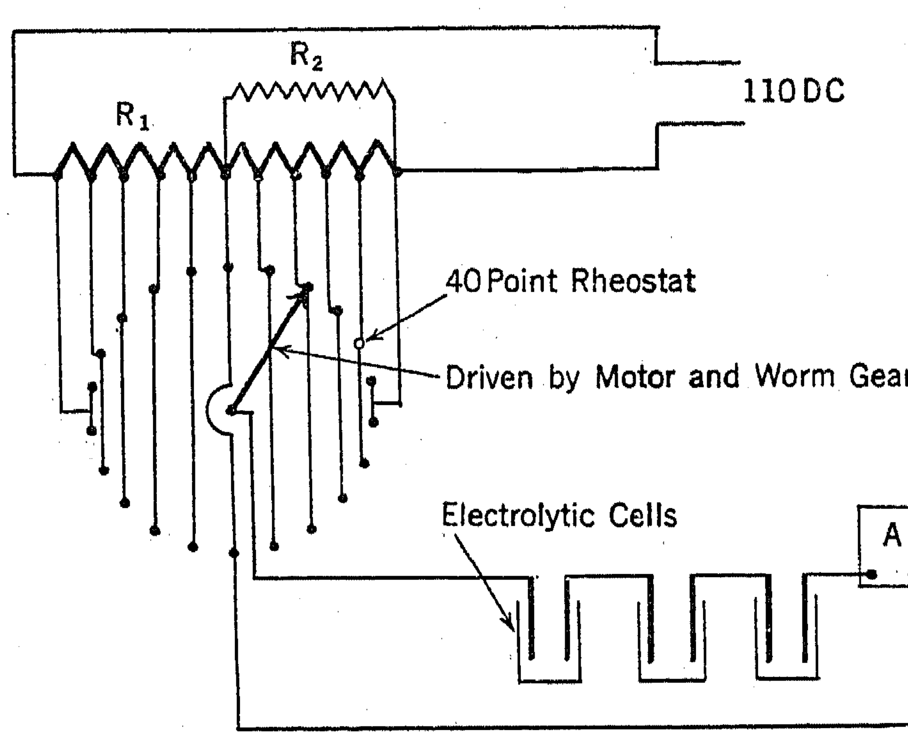


FIG. 7

The resistance R^2 (Fig. 7) was introduced to correct a slight dissymmetry in the positive and negative halves of the current wave. This device was substituted for the reversing switch because it was difficult to make the time of closure of the switch the same for both directions and because for this particular investigation it was desired to have the wave form approximately that of a sine. The average value of the current was determined by an integrating d-c. ammeter which was reversed each half cycle. The ratio between the maximum current and this average was calculated and considered constant for the several succeeding tests. The equality of the positive and negative halves of the current wave was checked by means of a copper voltammeter.

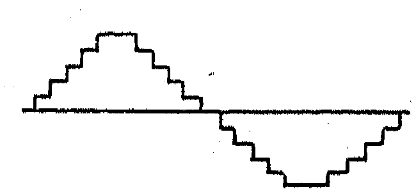


FIG. 8

These tests induced us to arrive at the following conclusions:

(a) The lower the frequency the greater the loss in weight of the electrodes, this loss increasing very rapidly below 0.5 cycles per second.

(b) All of the substances investigated corroded very rapidly with d-c. currents.

(c) Where considerable chlorides are present in the electrolyte, ingot iron seems to be superior to any of the other substances investigated.

(d) With low frequencies, monel metal seems to be the most satisfactory with 2 per cent sodium carbonate solution.

(e) Boiler iron seems to have almost the same loss as ingot iron.

(f) Very large differences in loss were obtained depending on the condition of the surface of the plates. This may account for the peculiar increase in loss for the nichrome at 5.0 cycles (see Table I) as this material is especially susceptible to surface conditions.

Some previous investigators have thought that the electrode loss per ampere hour was a function of the current density. Where they have shown data to substantiate this, is it not possible that the greater current density produced a stirring action, which as pointed out by the authors of this paper, increases the loss.

Maximilian Toch: Under the heading "Complete Series of Tests," it is stated that the experiments were conducted with iron and lead buried in soils, and I believe no attention has been paid to the electrolyte in these soils, for the obvious reason that if steel or metal which will corrode is buried in a soil in which there is no oxygen nor water corrosion cannot ensue, and I have seen so many cases of subterranean corrosion, beams of buildings, pipes and conduits, that I know there is a vast difference between electrolytic corrosion in a wet soil and electrolytical and chemical corrosion in a semi-dry soil.

In fact, I have gone so thoroughly into this subject that I am even now conducting experiments on the western coast of South America in a climate which I believe is much dryer than that of Arizona, and I have conducted experiments in the southern part of Nevada and the northern part of Arizona on the protection of steel against corrosion under various conditions. I say this in order to qualify before you, for I have paid a great deal of attention to this subject in the last twenty-one years.

Burton McCollum: Mr. Torchio has raised the question as to why the principles brought out in the paper have not been heretofore applied by electric railway interests for the mitigation of electrolysis troubles. The reason I think is quite apparent, namely, that in order to secure anything like the high degree of protection that would be desired it would be necessary to reverse the polarity of the trolley several times a day, although of course, reversing once every 24 hours would accomplish something. To reverse the polarity of the trolley once an hour or oftener would introduce an operating complication that few if any, railway men would consider. Such frequent reversal would be objectionable even where an entire system is supplied by a single station, and would be practically prohibitive in the case of a railway system fed by several interconnected stations. It is largely for this reason I think that the work of Mr. Larsen has not been given more attention. I would point out in this connection that the work described in the present paper covers

an entirely different field and was undertaken for an entirely different purpose from the work done by Mr. Larsen. Mr. Larsen's object was to determine whether or not it would be feasible to reduce electrolysis trouble by a frequent reversal of the trolley polarity, and he carried out no experiments in which the current was reversed more frequently than once an hour. In the present investigation it was our aim to determine the order of magnitude of the corrosion that would be produced in the so-called neutral areas of railways where the reversal takes place at short intervals of from a few seconds to a few minutes. In order to make the investigation complete we carried out some experiments with alternating currents of ordinary frequency on which a good deal of work had previously been done, and also extended our investigation into the regions of long periods such as those adopted by Mr. Larsen. Between these extremes however, we have covered a wide range which has not heretofore been investigated, namely, frequencies of reversal such as those found between tracks and pipes and other underground structures in the so-called neutral areas of electric railways.

I wish to make it clear that the authors have not put forward this data with any idea that it will be used as the basis of a comprehensive system of electrolysis mitigation, and we do not consider that there is much likelihood of it being used in this way for the reasons pointed out above. Our principal purpose in bringing out the results of these tests is to show that in so-called neutral areas the actual amount of corrosion that will take place is much less than has often been supposed, and that the extension of the neutral areas due to the application of insulated return feeders, three-wire systems, and other methods of mitigating electrolysis troubles, need not be regarded as introducing any additional hazard to underground structures.

Regarding the criticism brought out by Prof. Ganz and Mr. Maxwell, I would say that the current density of 0.5 milliampere per sq. cm. was used for the reason that this is about the lowest value that is likely to be of any practical consequence. If the current density is 0.5 milliampere per sq. cm. the actual rate at which the iron would be corroded away would be approximately one centimeter in 12 years. This is a rate of corrosion which is frequently encountered in practise where electrolysis conditions are only moderately severe. Much higher current densities are frequently found, however. On the other hand, it is perfectly true, as Mr. Maxwell and Prof. Ganz have pointed out, that in practise, especially near the so-called neutral zones, the current density may often be but a very small fraction of that used in the tests, but it must be admitted that such current densities are of no practical importance. For instance, if we use a current density of 0.0046 milliampere per sq. cm., which Mr. Maxwell states has been actually found by him, it would appear that it would take about 1300 years to corrode the iron

to a depth of one centimeter. While it may be true that the effect of reversed currents with these low current densities may be very different from that observed in these experiments, it is evident that the rate of corrosion in any case will be so low that it is of no concern from a practical standpoint, however interesting it might be from a purely scientific point of view. In this connection I would say that the corrosion on the test specimens used by the authors, while not strictly uniform, was nevertheless so well distributed over the surface that it was evident that the current density at any one point was not very greatly in excess of the average value of 0.5 milliamperes per sq. cm. used in these tests.

Prof. Ganz states that the tests were made in only one kind of soil. This is quite true. Part of the tests were made in the natural soil and some with sodium carbonate added, and the results, while slightly different, indicate the same general law. It is not improbable that with soil from different sources it would be found that the knee of the corrosion curve, or the point at which it begins to rise abruptly, would be shifted more or less. Nevertheless all of the experiments made indicate that the effects would be of the same general character as here observed.

Prof. Ganz quoted some figures from the table and seemed to convey the impression that they are misleading. For example, he stated that the table shows that with a ten minute reversal in the case of lead the coefficient of corrosion given is 0.132, and he appeared to assume that this is intended to show that the ratio of the corrosion on this frequency to the corrosion on direct current would be 0.132. This error might readily creep in provided the authors did not give the actual corrosion on direct current, but since this is given and shown to be approximately 0.25 I do not see how any one could be misled as to the magnitude of the reduction in corrosion produced by the reversals.

Prof. Ganz also suggested that in view of the fact that all of the experiments described in the paper were made with periodically reversed currents in which the algebraic average was zero, that it would be desirable to make additional experiments with unsymmetrical alternating currents in which the algebraic average is not zero. This I think is a good suggestion and I hope that it may be possible to make such experiments in the near future.

Mr. Way described a plan which he expects to try out whereby he hopes to utilize the principles set forth in the paper for reducing electrolysis troubles. If I understand his plan correctly, it would amount to superposing on a unidirectional current a symmetrical alternating current of sufficient magnitude to reverse periodically the polarity of the pipe. This would not have the effect of reducing the algebraic average of the current, so that if I have not misunderstood his plan I do not see how it would materially reduce electrolysis troubles.

Mr. Chubb suggests that possibly the positive and negative

half waves were not equal and that this may in part account for the large discrepancy in some cases between the corrosion of the odd and even electrodes. This seems very unlikely since great care was taken to avoid any error of this sort. An oscillographic record carefully analyzed in a considerable number of cases did not reveal any appreciable unbalance.

I have been particularly interested in the results presented by Mr. Spooner as they were made under different conditions using a liquid electrolyte instead of soil, but nevertheless the results obtained on ingot iron are substantially in accord with the results presented in our paper.

Presented at the 320th meeting of the American Institute of Electrical Engineers, New York, April 14, 1916.

HIGH-VOLTAGE D-C. RAILWAY PRACTISE

BY CLARENCE RENSHAW

ABSTRACT OF PAPER

During the past 10 years, the operation of electric railways at d-c. voltages of 1200 and 1500 has become common and higher voltages have been shown to be practicable. The paper deals first with the fundamental differences in apparatus for 1200 or 1500 volts as compared with the former 600-volt standards and indicates the apparent tendency of general practise with regard to a number of alternative constructions which must usually be considered in each specific application of these systems.

Referring then to the use of higher d-c. voltages which is just beginning, it points out the tendency to reach an ultimate maximum by employing a multiplicity of voltages differing but slightly from each other, such as 2400, 3000, 3600, 4200, etc, for successive installations. It recommends, in order to avoid the confusion which must surely result from this, that efforts be made to establish at once a single standard for high-voltage lines.

The paper shows that final standards in voltage are usually fixed by broad economic considerations rather than by physical limitations and suggests that 5000 volts direct current would offer a very satisfactory voltage for such a standard if commercial apparatus for this voltage were available. Finally, it touches briefly upon the operation of the experimental 5000-volt line at Jackson, Michigan, which has been so successful as to give great hope that the system will be commercially developed.

TEN YEARS ago, the idea that approximately 600 volts was the maximum potential to be hoped for in the operation of d-c. railways was almost as firmly established as was the belief in the days of Columbus that the earth was flat. On a few roads, it is true, 650 or even 700 volts was carried at the station and in an occasional rare instance, the use of a booster gave a maximum of 800 or 900 volts. Drop in the feeders, however, usually reduced these values considerably before they reached the car, so that these instances represented merely the generation of d-c. power at voltages above the nominal 600 rather than its utilization by the car motors.

Then suddenly the plan was suggested of coupling the four 600-volt motors ordinarily employed on interurban cars in pairs of two in series instead of two in parallel, and of connecting the generators in the stations in a similar manner, so as to employ

1200 instead of 600 volts. Two railways then under construction were willing to try the scheme, and although there were some misgivings as to whether it would work or not, it did. The entire railway industry as a result has been given a lesson in open-mindedness which it should not soon forget and the use of d-c. voltages of from 1200 to 1500 for the operation of interurban railways has become so common that today we are able to discuss details of high-voltage d-c. practise.

Motors

Limiting ourselves for the time being to voltages of 1200 and 1500 in discussing the matter, the first element to be considered of a high-voltage car or locomotive equipment is of course the motor. As far as voltage between terminals is concerned, the requirements for motors to operate two in series on such voltages differ from those for low-voltage service only in the fact that slipping of the wheels to which one of the two motors in series is connected may interfere with the normal voltage distribution between them, and concentrate a large part of the total voltage at the terminals of one machine. Fear of this contingency at first led to the design of motors for high-voltage service with a much larger number of commutator bars than for corresponding 600-volt service. More extended experience, however, showed that such precautions were unnecessary.

Insulation and creeping distances on motors for high-voltage service must of course be made suitable for the full potential. This was accomplished at first by "main strength and awkwardness," as it were, and the limitations imposed by the extra insulation, extra creeping distances and extra commutator bars ordinarily carried with them a considerable sacrifice in capacity when a given motor was wound for operating two in series on 1200 volts instead of two in parallel on 600. As in the matter of commutator bars, however, wider experience gradually overcame this difficulty. The extra insulation required for 1200-volt operation is now obtained by the use of better quality rather than greater quantity of material, and the extra distances by improved shaping and arrangement of parts. Generally speaking, therefore, motors are produced today for use in series on 1200 or 1500 volts with the same dimensions and weights as if made for use on only 600 or 750 volts.

In referring to motors above, I have spoken as if the coupling of two 600- or 750-volt motors in series was the only arrange-

ment ever employed for utilizing 1200 or 1500 volts. There have been, however, one or two instances where motors have been wound directly for the full line potential. Speaking generally, such motors are heavier and depart more radically from standard low-voltage designs than motors for operating two in series, and moreover, they do not lend themselves as well to the operation of the cars partly on 600 and partly on 1200 volts, which is so often required. In general, therefore, they seem to offer no particular advantages and are hence but little employed.

High-voltage d-c. railway practise, therefore, in the matter of motors may be said to consist in the use of two machines in series, these being identical in construction with standard motors for low-voltage service except in the comparatively minor details of quality of insulation and length of creeping distances.

Control

In control apparatus for high-voltage d-c. railway equipments, the fundamental requirements are to provide sufficient circuit-opening capacity to overcome the greater tendency to "hang" which the high-voltage arcs possess, together with the necessary means to confine these arcs within proper bounds.

The first result was secured in the early high-voltage apparatus by using two 600-volt switches in series at practically every circuit-opening point, and the second by liberal increases in the insulation and space surrounding all live parts. Thus our first 1200- and 1500-volt car equipments employed 13 pneumatically-operated switches, where with the same current at 600 volts eight would have been sufficient. The groups in which these switches were assembled, also, were approximately 24 in. (60.9 cm.) wide and 24 in. deep as compared with 18 in. (45.7 cm.) wide and 22 in. (55.8 cm.) deep for the corresponding 600-volt apparatus.

As with the motors, however, greater experience led to a reduction of these differences in the fundamental parts. Some of the extra switches in the first equipments came into play only when the controller was "backed off" from parallel to series, and by improvements in interlocking the work of opening the circuit at this time was transferred to another point so that these extra switches could be omitted. Another switch had been employed because it was feared that the high-voltage motors might require more careful handling and hence more resistance

notches than standard 600-volt motors. It was found later that such was not the case and this switch also was omitted in future equipments. In these ways, in the types of equipment most generally employed, the additional switches necessary on account of the increased voltage have now been cut down to two for small equipments or three for large ones. In dimensions also, it has been possible to work out designs for 1200-volt switch groups with the same cross-sectional area and the same weight per switch as those for 600 volts.

Auxiliary Control Devices. The introduction of the new element of operating at double voltage has greatly increased the number of possible combinations and alternatives which must be considered in any given case in order that they may be adopted or rejected.

In the first equipments for use on 1200 volts, it was considered undesirable to attempt to employ this voltage for the auxiliary circuits such as lights, control, air compressor, etc., and so a dynamotor was included as a part of the equipment to provide a supply of 600-volt current for such purposes. To reduce the capacity required of the dynamotor, the air-compressor motor was next wound for operating at full line potential, so that only the lighting and control circuits need be supplied at 600 volts. Even on this basis, the presence of the dynamotor in addition to the air compressor seemed unnecessarily burdensome, so that the next step was to combine the two machines in a dynamotor compressor. In this device, the air compressor, instead of being driven by a separate motor, as previously, is connected to or disconnected from the dynamotor when required by a suitable clutch controlled by the pressure governor. In locomotives or other equipments where forced ventilation is required, the operation is still further consolidated by mounting the blower fan on the shaft of the dynamotor so that the same machine in such cases serves a triple purpose. This offers considerable advantage in simplifying equipments, and the scheme of driving the compressor and providing 600-volt current for the auxiliary circuits from the same machine has become firmly established in high-voltage practise.

Where equipments are to be mounted on cars of small or moderate size, however, even this arrangement is somewhat of a handicap in the matter of cost and simplicity when comparison is made with the usual 600-volt equipment of the same capacity, so the next step was to arrange the lighting and control

circuits for operation directly from the line voltage. With electropneumatically-operated control, this was readily done and on such a basis, 1200- or 1500-volt equipments have been made practically as simple, reliable and easy to maintain as those for operation on 600 volts.

As the art now stands, these two general arrangements for handling the auxiliary circuits constitute a dual standard and one of the first decisions to be made in planning any given installation is between these two schemes.

Operation on Two Voltages. The most prolific source of vexatious problems is the use of equipments part of the time on low voltage and part of the time on high. As far as the main-circuit apparatus is concerned, any high-voltage equipment will of course run on half voltage with a corresponding reduction in speed. In order that such operation may be satisfactory, however, special arrangements must be made to care for the auxiliary circuits.

Many interurban lines operate at high speeds over their own rights-of-way in the open country but enter one or more towns over the tracks of local 600-volt systems. High speed in the city is not permissible in any case and so approximately half of the normal speed when running on 600 volts is sufficient. For cars operating under such circumstances, it is common to provide for reconnecting the lighting and control circuits so that these will receive full voltage when the car is in the 600-volt section but so that the main motors will remain permanently coupled in series and thus operate at half speed.

If a dynamotor compressor is employed on cars which operate in this way, the same changes which are necessary in any case to care for the lighting and control circuits automatically care for the air compressor as well, connecting this for full speed on both voltages. In cases where approximately half speed on low voltage is sufficient for the main motors, however, the distances are usually short and half speed of the air compressor also is sufficient. Where cars which operate in this way employ a high-voltage compressor instead of a dynamotor compressor, therefore, no change is ordinarily necessary in its circuits for the low-voltage operation.

Since the motors on high-voltage cars are in general wound for only 600 or 750 volts each, the car can if desired be arranged to operate at full speed on both high and low voltage. Where this is required, a main change-over switch is employed which

connects the motors of each pair either in series for high voltage or in parallel for low voltage, and which connects the two halves of each step of the main resistance in a corresponding way. Suitable connections for air compressor, lights and control circuits can also be included in the same switch so that the setting of a single piece of apparatus into one or the other of two positions changes the car at once for use on high voltage or on low voltage.

When the proper scheme of operation on the two voltages has been decided, the next point to determine is the manner in which the change-over should be effected. The simplest method in either case of course is the use of a manually-operated switch on each car. It is sometimes desirable, however, to have the change-over switch located beneath the car and arranged for operation from the platform. In other cases, it is desirable to have the switches arranged not only for distant control in this way but also for simultaneous operation throughout a train of cars.

To supplement the apparatus for changing connections on equipments so that they may be operated on either high or low voltage, protective devices are sometimes desired to prevent or minimize the trouble which may occur in case a car is subjected to high-voltage when its change-over switch is arranged in the low-voltage position. Such devices ordinarily consist of relays of some form which are so connected, when the change-over switch is in the low-voltage position, that they act quickly in case a voltage in excess of the normal is applied to the car, and cut off the circuits which are likely to be damaged.

The choice between automatic and non-automatic acceleration is not influenced particularly by the use of high voltages except that such voltages are more often employed for interurban lines where non-automatic acceleration is ordinarily considered preferable. The necessity for running on both 600 and 1200 volts in many cases also usually introduces certain complications in high-voltage equipments and there is a tendency to adhere to non-automatic control so that the simplicity of this will, as far as possible, offset the various complications which must be retained.

The use of field control or non-field control also is not particularly affected by the employment of high voltages except as influenced by the same general idea mentioned above with regard to the choice in the type of acceleration. For the sake

of simplicity, there is a tendency to adhere to non-field control to offset unavoidable complications at other points.

Alternatives in Control Apparatus. It will be seen from the above that even with common practise in high-voltage equipment fairly well standardized, a host of alternatives usually present themselves for settlement in almost every case. The most common questions are—should the voltage be 1200 or 1500; should the equipment be of the dynamotor compressor or of the non-dynamotor type; will it have to operate on high voltage only or on both high and low voltage; if required to operate on low voltage as well as high, will half speed be sufficient on main and compressor motors or will full speed on both voltages be necessary; must the change-over switch be arranged for indirect control or will manual operation be sufficient; if indirect control is required, can it be confined to the individual cars or will simultaneous operation throughout the train be required; is a protective device essential to guard against damage by the application of the wrong voltage or will this not be required? Other similar questions might be added to the list but these are the most important ones.

Most of these matters are largely influenced by the individuals who control the local situation, so that it is difficult to generalize with any degree of accuracy. As far as I can judge, however, current practise seems to be tending in the following directions.

Where the high-voltage cars must run over existing 600-volt lines to any considerable extent, the exact ratio between 600 and 1200 volts offers some advantages. Since high-voltage motors are made from existing standards also, there is a wider range of choice for 1200-volt operation than there is for 1500 volts, especially where small sizes of motors are required. So far, 1500 volts has been used in sections where 600-volt lines have been established only to a limited extent, that is, in comparatively virgin territory, while 1200 volts has been employed in sections where there has already been considerable 600-volt development. It seems probable that high-voltage practise will continue to follow these lines except in the case of the electrification of branch lines on steam railroads or similar instances where connections with existing lines will have little bearing.

Speaking broadly, the general tendency is toward the use of the dynamotor compressor on large expensive cars, particularly

where full speed is required on half voltage, since this arrangement lends itself readily to such operation. Dynamotor compressors also are particularly suitable for locomotives where forced ventilation is utilized. For smaller and less expensive rolling stock, non-dynamotor outfits are generally employed, although there is and always will be a certain amount of overlapping.

In the older sections of the country where distances of four or five miles must sometimes be run on city tracks, and where through cars over 600-volt lines are likely to be employed, equipments are usually required to operate at full speed on half voltage. Equipments for operating at half speed under these circumstances, however, offer considerable advantage in weight, cost and general simplicity and will undoubtedly find a considerable field where circumstances are favorable to their use.

Where large cars are arranged for full speed on both voltages, the tendency is toward the use of full speed for the air compressor also. On smaller cars where as a rule the compressor has more margin, half speed of this device is ordinarily thought sufficient even where the main motors operate at full speed.

In the matter of change-over switches, the general tendency is to employ the simple manually-operated type except where cars are operated at close headway or are constantly used in trains. In most cases, also devices to protect against the wrong voltage are not considered necessary.

Equipments with Drum Control. I have spoken in all of the above with particular reference to equipments using indirect or multiple unit types of control and primarily with reference to those using electropneumatic control. While high-voltage equipments are occasionally used with drum-type controllers, especially double equipments with rheostatic control where cars for city service are operated in small towns by interurban companies, the number of these is too small to warrant inclusion in any generalization such as that with which we have been dealing.

Power Supply

Direct-current power for high-voltage lines was first obtained by the use of two 600-volt generators, either engine- or motor-driven, connected in series. Since there was no particular object in retaining two generators in series such as there was for retaining two motors in series on the cars, generators for

delivering 1200 or 1500 volts directly were soon produced. At first these were of the ordinary commutating-pole type. Such machines now, however, usually employ a compensating winding as well as commutating poles.

The next step in the production of high-voltage d-c. power was the use of two 600-volt, 25-cycle synchronous converters connected in series, and while this was considered a radical step at the time it was first proposed, the performance obtained was so satisfactory that single 25-cycle converters producing 1200 or 1500 volts on one commutator have now been developed and are in successful use. With 60 cycles, the maximum voltage so far employed from a single machine is 750 so that two machines in series are still required for high-voltage lines. The performance on this basis, however, is most excellent.

Common substation practise for high-voltage d-c. lines is now to employ single synchronous converters where power at 25-cycles is available, and to use either motor-generator sets or two converters in series, where 60-cycle power is employed. A particularly efficient substation arrangement on the latter basis is secured by installing three synchronous converters so arranged that any two of them may be connected in series. This gives a spare machine at a minimum expense. If a single bank of three transformers is used for supplying these converters, a spare transformer as well as a spare converter is also secured, so that the station is prepared for almost any emergency.

Switching

In the matter of switching, the principal changes which have been made in handling current at 1200 or 1500 volts instead of at 600 volts have been for the purpose of insuring safety to the operators rather than for any other reasons. For this purpose, switchboard panels have been made higher than for 600-volt service and the circuit breakers located on them so as to be out of direct reach. For opening and closing the breakers, long wooden rods leading to insulated handles on the lower part of the panel, are provided. Where two or more breakers are located side by side, large barriers are placed between them to prevent any tendency to flash across. Knife switches have also been located out of reach in a manner similar to the circuit breakers and arranged with rods for distant control.

Line Construction

The first 1200-volt lines employed direct-suspension overhead trolley with a special form of porcelain insulators. The catenary form of construction offers so many advantages for such lines, however, that generally speaking, the most common practise is now to employ this. Several interurban lines are using 1200-volt third rail successfully for supplying power but the voltage surges to which this may give rise under certain circumstances, the difficulty of clearing a car in case of accident and the general safety hazard incident to the maintenance of a live conductor so close to the ground seem likely to limit the use of this form of construction.

A growing practise on high-voltage systems is that of carrying the feeders for a considerable distance from the station before tapping in to the trolley so as to limit the possible current flow in case of trouble of any kind on the cars. With the excellent voltage conditions which can so easily be secured on high-voltage lines, the slight sacrifice which need be made for the sake of protecting the substation apparatus in this way can usually be well afforded.

Economic Significance

In studying the development of 1200- and 1500-volt practise, the fundamental point which appeals to me is the ease, success and speed with which so radical a departure from previous practise has been carried out. In most developments of so far-reaching a nature, many sources of difficulty are usually overlooked at first and must be cared for in later apparatus at increased expense. In the high-voltage d-c. railway system, however, just the opposite has apparently happened. Many of the possible difficulties seem to have been over-estimated in importance and much of the trouble anticipated has failed to appear. It has therefore been possible to gradually simplify and cheapen the various fundamental parts which go to make up the system instead of having to follow the opposite and more usual procedure.

It is difficult to say whether this exceedingly gratifying condition was due to the more advanced engineering ability of the times, to the inherent simplicity of the d-c. railway apparatus, to the very excellent state which such apparatus for 600-volts had reached before its extension to higher voltages was attempted, or to the fact that the jump to 1200 or 1500 volts, while seemingly radical, really subjected the apparatus to conditions differing

comparatively little from those met with in 600-volt practise. Whatever the cause may have been, however, the result remains as a remarkable tribute to those who shared in its accomplishment.

The general results of the high-voltage d-c. system have been to make possible the construction of interurban lines or the electrification of branch steam railroad lines at considerably less expense for a given grade of construction than with 600 volts, or to render possible for a given expenditure the construction of lines capable of handling much heavier traffic. The usual practise has apparently been a compromise between these two possibilities, which has served to finally transfer the electric line from the street car to the real railroad class as far as transportation possibilities are concerned, while still maintaining the relationship and similarity with reference to the simplicity and reliability of the apparatus. With practically no greater expenditure for substations and feeders than the usual 600-volt trolley line, such roads are able to employ freight or passenger trains after the manner of steam lines in accordance with the needs of their business instead of having to restrict them on account of limitations in the distribution of power.

2400 and 3000 Volts

The comparative ease with which the use of 1200- and 1500-volt direct current was transferred from the realms of uncertainty to the list of every-day standards soon suggested the employment of still higher voltages. Inasmuch as the 1200-volt system had been brought about by the use of two 600-volt motors in series and as a few motors wound directly for this voltage had been produced with no particular difficulty, the obvious procedure was to continue the geometric progression and connect 1200-volt motors and generators in series so as to operate at 2400 volts.

From a technical standpoint, there was apparently no particular difficulty in doing this, and one line installed on this basis has had a remarkably successful record. From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking. For trolley roads of the usual interurban class, it has the inherent disadvantage of requiring apparatus which departs too widely from the existing standards with which the

operating forces have become familiar, as well as of not lending itself to interchangeable operation over 600-volt lines. For heavy traction, on the other hand, this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, does not do so completely. It is regrettable also that *both* 2400 and 3000 volts have been employed and that in carrying on the upward progress in d-c. voltages, 1500-volt apparatus was not used at once for coupling in series, for carrying on the geometric progression, without the intermediate 2400-volt step.

Ultimate Limits of D-C. Voltage

The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations. It is entirely possible for instance to operate trains at maximum speeds of 90 miles per hour or more, yet the maximum ordinarily attained is from 60 to 80 miles per hour. Physically speaking, also, interurban cars can be run at speeds similar to these, yet the general average on such roads is from 50 to 60 miles per hour. These values have been established by gradual increases from lower ones until without any conscious effort, standardization has been automatically secured.

In the voltages which may be employed with the d-c. railway system, there is some tendency toward this same procedure. If no efforts were made to the contrary, it is not improbable that starting from the voltage of 3000, which we have today on the Chicago, Milwaukee & St. Paul, we would next hear of the employment of 3600 volts, then possibly 4200 volts and so on up in corresponding steps. Sooner or later, however, a point would be reached where, by common consent, these increases would stop, just as this has happened in the matter of speed.

While in a way, such a procedure would be the conservative and natural way for progress to come about in the use of higher d-c. voltages, its disadvantages are too obvious to require mention. The apparently more radical plan of trying to select in advance the voltage at which such increases would naturally stop and of going at once to this voltage would hence seem to be the more rational and really the more conservative as far as the general good of the industry is concerned. It has been

with this idea in view that our efforts toward the use of direct current at 5000 volts are being put forth. With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotives likely to be required can be readily solved so that although further increases might be possible, they should be entirely unnecessary.

Operation of 5000-Volt Equipment

The general construction of the 5000-volt experimental equipment on the Grass Lake line of the Michigan United Traction Co. and the results of its first few months' operation have been so widely covered by the technical press that it is unnecessary to refer further to them except to say that the equipment is still in operation on the same successful basis, and that at the time this is written, it has run a little over 30,000 miles. During the five months from October 1st to March 1st, the car averaged 5295 miles per month on a schedule which allows only 15 miles per hour and its record would have been even greater than this had it not been for numerous mechanical difficulties with the trucks, wheels, brake rigging, stove, pilots and other mechanical parts of the car for which the equipment was in no way responsible. During the four months of November, December, January and February, which, on account of weather conditions, are ordinarily considered the worst in the year, the car ran 23,320 miles or an average of 5830 per month.

During this period the car operated through severe snow, sleet and rain storms and for a short period even ran with two of the commutator covers missing, these having been lost on the road. The motors and control were purposely allowed to go with a minimum of cleaning and other care, and various reports sent in by the men in charge refer to the presence of wheel wash, dirt and other obnoxious substances in the motors and switch groups, although no damage was caused by them.

A half-dozen or so failures have occurred during the winter but these have been mostly in the nature of broken motor leads or similar troubles which served merely to test the practicability of the use of such a voltage under the general rough conditions to which car equipments are subjected rather than to indicate any inherent weakness. These troubles showed that this equipment could as easily withstand such ordinary mishaps

as any equipment for 600 volts. Only two of the failures were in any way due to the use of 5000 volts and these consisted of grounds on the grid resistance which took place through the water-soaked flame-proof covering on certain of the leads where the cables had not been properly insulated and supported. Such troubles can be easily guarded against on new equipments.

While as yet only the one equipment now in experimental operation has been built, various designs of other sizes have been considered and with the special double-armature type of motor and double-jaw type of switch which have made this equipment possible, unusual flexibility in meeting a wide range of conditions can apparently be obtained.

In most of the considerations of the use of d-c. voltages of 2400 and 3000, there has always been a certain minimum size of motor which could be economically produced and this size has been undesirably large for certain classes of service. With the special double-armature type of motor for 5000-volt equipments, however, the experimental equipment already in use is about as small as would ordinarily be required, although even this is apparently not the minimum limit. On the other hand, the design seems equally adaptable to large sizes.

Conclusion

Broadly viewing the high-voltage d-c. practise which we find today, and its significance to the industry, there are four ideas which appeal particularly to me. The pernicious flexibility of the 1200- and 1500-volt systems and the innumerable alternatives which they present for application to any definite case in interurban work, seem to give timely warning of the great desirability of early standardization in the matter of higher d-c. voltages. The comparative ease with which apparatus for these voltages has been developed gives a most encouraging feeling for further development along the same lines. The possibilities which a d-c. system at 5000 volts would offer were the apparatus commercially available make this voltage seem a logical one and the results obtained with the experimental equipment now in operation give great hope that this voltage may some day be established commercially as a standard of high-voltage d-c. railway practise.

DISCUSSION ON "HIGH-VOLTAGE D-C. RAILWAY PRACTISE (RENSHAW), NEW YORK, APRIL 14, 1916

Frank J. Sprague:* Mr. Renshaw states that ten years ago the idea of approximately 600 volts as the maximum potential to be hoped for in d-c. railway operation was firmly established. I can claim that some engineers at least were not deluded with this conviction.

In the early days of stationary motor development I had built some special machines to operate normally at from 500 to 600 volts but which in the exigencies of service had been boosted to about 1000 volts; and on the 34th Street branch of the Manhattan Elevated in the latter half of 1886, where a number of the primary features of the modern electric railway were tried out, I operated at 600 volts from a third rail.

When, a year later, I took the contract for the pioneer trolley roads at Richmond and St. Joseph, I adopted a somewhat lower potential, 450 to 500 volts, which pressure and system were, however, even then regarded as extreme. This standard was gradually raised, however, to about 600 volts, and remained there for practically twenty years.

In February, 1890, at the Kansas City Electric Light Convention I stated, as follows:

"As regards the potential, other things being satisfactory, whatever pressure is demanded in the interests of economical and effective service will be used; and means will be found, consisting mainly in care of construction, which will make its use for the purpose, and as intended, safe and proper. We have in these matters to face the same questions as we have in the matter of steam pressure or of railway speed. To accomplish the larger engineering feats necessary to meet the demands of economy and commerce we will be governed more by the belief in our power to fully subordinate a good servant to our will than by our fears of its vagaries when allowed to become a master."

In my inaugural address as President of this Institute at the Chicago Meeting, June 18, 1892, I pointed out that we were at that time, if using d-c. motors, practically limited to a difference of potential of from 1000 to 1200 volts, and that to go above that limit it would probably be necessary to put motors in series as I had sometime before proposed for long distance power transmission.

In March of 1904, in an article in the *Electric World and Engineer*, I said:

"While d-c. motors may always be somewhat at a disadvantage in the matter of individual potential, when there is a plurality of motors, as in the large locomotive, it is quite possible on a d-c. system to work up to 1700 or even 2000 volts on a single trolley line, maintaining a maximum as in regular use on the Berlin Elevated, of from 850 to 1000 volts on individual motors; and if a three-wire system be used it is quite possible to make use of a maximum trolley potential of nearly 4000 volts."

*Abstract of discussion published in August, 1916, PROCEEDINGS.

On the introduction of the interpole in stationary motor construction, I recognized the benefits of this construction for railway motors and advocated its adoption, pointing out that it would make possible an immediate increase in potential for direct-current railway work from 1200 to 2400 volts, without question.

In 1906 I urged upon the engineers of the Washington, Baltimore and Annapolis line the adoption of 1200-volt d-c. operation, and in the fall of the same year, I recommended to the consulting engineer of the Central California Traction Company the use of a 1200-volt d-c. third rail. My recommendation was adopted and the installation, the first of the kind, went ahead on this basis.

A month later I discussed quite fully the details of the 1200-volt operation with the consulting engineer of the Southern Pacific Railway Company, and recommended this potential for the Oakland suburban lines of the Southern Pacific system.

In a discussion before the American Institute of Civil Engineers in Nov., 1906, I called attention to the fact that, comparing the condition of the art then and a couple of years earlier, three important and radical developments had taken place in d-c. motor construction, the first of which was the use of the commutating poles, which, with additional facilities in control, made perfectly possible the construction of d-c. motors at from 1200 to 1500 volts, with the further possibility of operating two in series at double potential.

The remarkable departure in the construction of the New York Central gearless locomotives, in which the hitherto invariable practise of maintaining the fixity of relation between the armature and the field magnet has been abandoned, gave me occasion to point out that this machine was a natural 1200-volt machine without commutating poles.

In 1906, after a personal inspection of the Sacramento Division of the Southern Pacific Railroad, I recommended an electrical equipment operated with an initial potential of 1500 volts at the substation third-rail junction, and described the possibilities of electrical braking, both direct and regenerative, through the use of independently excited fields as now used on the Chicago, Milwaukee and St. Paul equipment.

In my early experiments on the Manhattan Elevated in 1886, I used, for the field as well as armature, rheostatic control for speed variations. I described a plan of regenerative as well as direct electrical braking before the Boston Society of Arts in 1885.

In the *London Times and Engineering Supplement* of April 10th, 1907, Mr. H. M. Hobart made a curiously exact prophecy, as follows:

"My opinion is that within ten years, continuous-current systems as applied to railway electrification will employ line pressure more of the nature of 2000 or 3000 volts, and these systems will, in all probability, have come into extended use."

This is the year 1916. For practically twenty years the potential for d-c. railways remained unchanged at 600 volts. In ten years it has jumped to 3000 volts on the Chicago, Milwaukee and St. Paul Railway, one of the typically most difficult, and embracing in its 437 miles of line more route mileage than all the trunk line electrifications in the world. The 11,000-volt 15-cycle system is non-existent in this country, and not a new single-phase railway motor is now installed here except on the few systems remaining.

William J. Davis, Jr.: I do not think the Southern Pacific electrification presents any new problems at all. The discussion to-night seems to be along the lines of increases in voltage far beyond those used on the Southern Pacific. The Southern Pacific electrification has been in operation about seven years, and the success of the installation has been very marked.

As regards the tendency to higher voltages, it would appear that the proper voltage to be chosen for a given installation would depend upon the maximum tonnage to be hauled and limitations as to speed. The tonnage capacity of a system is dependent, we may say, upon the number of tracks that are in service. In a single-track road, if heavy tonnages are to be handled, it will be necessary to adopt higher voltages than would be necessary for a road having sufficient traffic to require two or three or possibly four tracks. In the case of a four-track road, all the tracks being in multiple, the drop in voltage in the track is greatly reduced, and we also obtain the advantage of the copper trolley wire or third rail for all four tracks in multiple, so that even when locomotives of very large powers are used, say 3000 or 4000 horse power it will be found in so far as the distribution system is concerned, that a moderate voltage, possibly 1200 or 1500, would prove as effective in handling the traffic as would 3000 volts, or more, in the case of a single-track or double-track road.

In a reduced number of tracks, some economy is gained in going to higher voltages, but the exact and most desirable voltage would depend not only on the saving in the amount of copper, but also on the load factor on the substations and the cost and number of locomotives required to handle the traffic.

In a single-track freight road, it will be found that upon the basis of the weight of trains now in use, very little improvement in load factor is secured if the substations are placed more than thirty or thirty-five miles apart. With this spacing, the copper required for delivering 3000 or 4000 horse power to a train is not at all excessive at 3000 volts, and is fixed almost as much by mechanical reasons and current carrying capacity as by the desire to secure a low drop in voltage.

Substation capacity also as applying to the whole system is not materially reduced, for the reason that the synchronous converters and motor generator sets are usually designed to stand three times normal load for a short time, and so long as

at least 33 per cent load-factor is secured there will be no saving in the total amount of substation apparatus.

The whole problem, therefore, appears to be narrowed down to the question as to the number of locomotives required on a given division and their cost. As a general rule, the cost of the locomotives required for handling the traffic of a single-track road will amount to about one-third of the total cost of the electrification. If, therefore, there is a material increase in the cost of a 5000-volt locomotive as compared with one for 3000 volts, this increase in cost may prove the determining factor. In the case of the Milwaukee electrification, forty-two locomotives were required, and an increase in their cost of fifteen per cent, due to an increase in voltage, would exceed the total cost of feeder copper for the entire system as required for 3000 volts. In the case of a double-track road in which the locomotives would be greatly increased in number, this difference would be still more marked, and would point to limitations of voltage possibly not exceeding 3000 volts as applying to most of the heavy freight traffic now obtaining on trunk line railroads.

William B. Potter: It is a pleasure to endorse much of what Mr. Renshaw has said as to the excellent features of high-voltage direct current. We are, however, rather more concerned with the future than with the past, and I think that the text of the ultimate is very well covered in his statement that: "The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations." He mentions as an illustration, that while it is possible to operate trains at higher speeds than the usual practise, it has not been found economically advisable to do so. I believe the question of higher d-c. voltages will be subject to the results of experience, and whether the limit will be 3000 or 5000 volts, or some other voltage, will ultimately be determined by "broad economic considerations."

In any railway electrification there are certain features which may be considered separately as parts of the general scheme. Under d-c. operation the initial cost, maintenance and depreciation of some of these features are but little affected by the operating voltage, while other features are so directly affected as to be a determining influence in the selection of voltage most favorable to economic results. The power station, high-tension transmission lines and track bonding are in the class of features first mentioned, and to a considerable extent, the substations as well. Sub-station equipment of established type generally increases in cost per kilowatt capacity with the increase in voltage for which it is designed; and while there would be fewer substations at higher voltages, the amount of included traffic usually becomes greater by reason of the longer distance between substations, and therefore there is little or no reduction in the total cost of substation equipment.

The two features principally affected by the choice of voltage

are the secondary distribution copper, including contact conductors and the rolling stock. A careful study of the respective merits of 3000 and 5000 volts was made in connection with the Chicago, Milwaukee and St. Paul electrification. There appeared to be little difference in the initial cost as a whole, the reduction in copper at the higher voltage being offset by increased cost of the locomotives. On the basis of 3000 volts the relative value of the different features in respect to each other may be illustrated by the following percentages: the high-tension transmission line complete, about 10 per cent; track bonding, 4 per cent; substations complete, about 18 per cent; the overhead construction, feeder copper and trolley complete, about 28 per cent; and the locomotives about 40 per cent. The 3000-volt copper for feeders and trolley only being something less than 20 per cent, and the locomotives being about 40 per cent it is not surprising that the reduction in copper at 5000 volts would have been offset by greater cost of the locomotive.

Considering depreciation and maintenance, it is better that an equivalent expenditure should be in copper rather than in locomotives which require maintenance and upkeep. To economize in copper and pay an equal amount for more expensive locomotives would be a transaction on the wrong side of the balance sheet.

Mr. Renshaw's comment with respect to 2400 and 3000 volts is in the main well taken. The Butte, Anaconda and Pacific might well have been 3000 volts. Occasions may arise, however, where the use of developed apparatus may be utilized to advantage at some other voltage than that for which it was originally designed,—a case in point is an electrification requiring locomotives with the same tractive power as those used on the Milwaukee, but at a speed of 12 instead of 15 miles an hour. It would be unnecessary expense to redesign this equipment for lower speeds when the same equipment at 2400 volts will give the speed desired.

Within the requirements of railway motor design multiples of 750 volts seem to be about the higher practical limit for advantageous winding. For the speeds usually required it is about as easy to wind a motor for 1500 as it is for 1000 volts, therefor multiples of 600 or 750 volts as a maximum naturally fall into line as the preferred voltages for d-c. operation

Mr. Renshaw in advocating 5000 volts makes this comment,—"With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotive likely to be required can be readily solved, so that although further increases might be possible they should be entirely unnecessary." There is at present no necessity for 5000 volts to successfully handle the distribution and collection of the necessary power for the largest locomotive likely to be required. The collection of power for the Milwaukee locomotives at 3000 volts is a complete success, there being no sign of arcing at the

contact between the pantagraph and the trolley wire in either freight or passenger service. Although the locomotives are equipped with two pantagraphs, a single one only is used; the current taken on the mountain grades being 800 to 1000 amperes, at 15 miles an hour by a single freight locomotive, and the same current at about 30 miles an hour in passenger service. The problem of successful current collection is greater at the higher speeds, and experimentally over 1500 amperes have been collected at over 60 miles an hour with a single pantagraph and no sign of arcing. The success on the Milwaukee is due both to the arrangement of the pantagraph collectors and method of supporting the contact conductor. Each pantagraph is provided with two collecting pans lined on the bearing surface with copper strips, and the contact conductor is two 4/0 copper wires which are in contact with each other in the same horizontal plane. The hangers supporting each of these contact conductors from the catenary are alternated so that the hanger of one conductor is midway the span of the other. The object of this arrangement of hangers being to minimize any inflexibility in the support of the conductors. For the successful collection of current without arcing it is absolutely essential at all speeds that intimate contact be maintained between the pantagraph and the contact conductor, and this can best be accomplished by so supporting the conductors with loop hangers, allowing freedom of vertical movement without the added inertia of the catenary. The upward pressure of the pantagraph should further be sufficient to slightly lift the contact conductors. The contact conductors are, therefore, lifted and carried free of the supporting catenary by the pantagraph in its passage. We found through a series of tests, that the wear of the pantagraph collector and the contact conductor was due not so much to the friction or mechanical wear as it was to the arcing due to collecting current, even an incipient arcing, so small as to be hardly visible, having a destructive effect. As an illustration, when collecting 1000 amperes, the rate of wear with 20-lbs. pressure against the contact conductor was about double what it proved to be at 30 lbs. pressure, the latter being the pressure adopted for the Milwaukee service. Running copper to copper we found, as might have been expected, that lubrication of the contact surfaces was essential to maintaining a smooth surface, and for this purpose a mixture of grease and graphite was used. It might be expected that lubrication would increase resistance of the contact surface. The most careful examination seemed to indicate that the conductivity is rather improved than otherwise. So far as we can judge from the tests, and from other lines operating under similar but less favorable conditions, the contact conductor on the Milwaukee will last for a number of million pantagraph passes.

There is no doubt that substation and locomotive equipment of 5000 volts can be successfully operated. The substation

equipment would not differ materially from a 3000-volt installation. The locomotive motors, however, because of the additional insulation required, and doubtless some change in the design would have less power for given size and weight, and in all probability, a greater number of motors would be required for a given service. The locomotive control equipment for 5000 volts seems to be principally a question of the additional space required for insulation and for the more extended arcing of the contactors. Experimental operation of the Butte, Anaconda and Pacific locomotives at 5000 volts gave opportunity of trying out the control devices under conditions approximating service operation. Arcing and flashovers at 3000 or 5000 volts are more startling, but seem to be even less destructive to the apparatus, than at 600 volts. The high-voltage arc seems to spread over more surface with less local burning than at the lower voltage.

The results of operation on the Milwaukee have been extremely gratifying. Nothing has occurred in connection with the use of 3000 volts that might not well have happened with 600 volts. Minor troubles have developed in the auxiliary devices, particularly on the locomotives, which are more annoying than serious, and can easily be corrected.

The regenerative feature of the Milwaukee locomotives has in every way been as successful as anticipated. The eastern grade of the Rocky Mountains is 2 per cent for 20 miles, and both freight and passenger trains are taken down this grade without air brakes more steadily and smoothly than they run even on the level, and without the delay incident to inspection of brake shoes and wheels as required when air brakes are used. On the lesser grades, where an occasional application of air brakes has formerly been required, regeneration is also made use of to control the train at whatever speed desired. The flexibility of d-c. regeneration makes it particularly suitable for the regulation of trains over a variable profile.

I quite agree with Mr. Sprague that it would be unwise to say that 3000 volts is a finality, and having in mind the economic problems that have to be dealt with, and that railroads are operated for profit, there would be even less wisdom in the arbitrary establishment of a standard not based on experience.

Calvert Townley: I can endorse the last speaker's remarks against the establishment of a standard voltage or trying to say now what shall be the limitations of future practise. I believe that the Institute and all engineers individually should encourage every possible advance in the art, and developments such as the one described in Mr. Renshaw's paper clearly indicate that substantial progress is still being made. Every improvement in fundamentals even if accompanied by some unfavorable construction limitations which are not fundamental should be welcomed and encouraged.

In commenting on the necessity for looking at every problem from all angles when selecting a system, the last speaker quite

properly favored a greater investment in the excess copper required by a lower voltage system and which depreciates very little, against the same amount put into the increased cost of the motors and auxiliaries of a higher voltage system where the maintenance and depreciation are both greater. It must be borne in mind, however, that a system which permits the use of a higher voltage scores a distinct fundamental and permanent advance in the art while whatever may be the present offsetting disabilities of increased equipment costs, these are largely temporary. We are just beginning to make 5000-volt equipments and 3000-volt equipments are not so very old. The history of all electrical development has shown that we may confidently expect improvements in design which will largely or entirely remove such temporary offsetting disabilities if any, as may now exist. One speaker cited the St. Paul Road as an example to prove that a 3000-volt trolley e.m.f. is high enough, concluding therefore that there is no use of trying to use higher pressures. He remarked that only one single 500,000-circular mil feeder is needed throughout the entire length of line. Without pausing to comment on the advisability of letting the entire service of a large railway system depend on one feeder it is interesting to note that a 500,000-circular mil bare copper feeder, 440 miles long, calls for over 3,500,000 pounds of copper, while with 5000 volts and with the same energy loss the investment in over 2,000,000 pounds of this copper would be unnecessary.

I feel very strongly that the Institute should welcome and in no sense attempt to decry any fundamental advance such as is described in the paper of the evening, and we should congratulate ourselves and the successful designers that such progress has been made possible.

While rejoicing at the recent rapid and marked increases in available continuous-current voltages, it is perhaps interesting to ask why this sudden activity—this very material advance after years of practically no progress when the limits seemed to have become rather firmly established? I find the answer largely in the increased demands of the new field of heavy railroad electrification and the development of the single-phase system which threatened to monopolize this field. The stimulus of competition has supplied the needed incentive to greater exertions in the study of continuous-current possibilities. If continuous-current apparatus was to receive serious consideration in heavy railroading it was necessary that every possible reduction in the excessive costs of that system should be made and every advantage taken of simplification of method. These conditions have not changed. It is still necessary for the continuous-current system to be bettered. A 3000-volt trolley is not good enough to more than incidentally share, much less to monopolize the heavy traction field against the alternating current. It is far from clear that even a 5000-volt trolley e.m.f. will be sufficient to prevail over available alternating-current systems but

it is however a long step in the right direction and we should welcome and encourage it in every possible way.

S. I. Oesterreicher: While in Mr. Renshaw's paper only general outlines of the underlying fundamental principles of high-tension d-c. railway practise are discussed, perhaps, it will not be out of place to mention certain details of modern d-c. railroad practise.

Mr. Renshaw does not mention storage batteries in connection with high-tension d-c. railroad work. From this I infer, that Mr. Renshaw does not deem it practical to consider such, for the voltages which are discussed in his paper.

While there are, no doubt, considerable difficulties about a floating battery on a say 3000-volt equipment, however it certainly would be worth while to investigate these difficulties for the sake of the advantages gained from the economic operation of the installation as a whole.

The greatest handicaps for such a storage battery project are purely commercial. Naturally this side of the problem must be determined, from case to case as it is presented, and for which no definite rules can be set down in advance.

From the technical side there can be no question, that it is entirely feasible to build and operate with perfect reliability a storage battery for any reasonable moderately high-tension voltage.

To give this statement some weight, I will cite a 1100-volt d-c. railroad equipment as designed by Mr. Fischer, chief engineer of the Budapest City Railroad Co. This company operated in 1912 about 56 miles of three branch lines, having a total of about 124 miles of tracks.

On one of these lines, with a length of about 30 miles, there are one generating and two substations. Power is generated at 11,000 volts, 42 cycles, 3 phase, and supplied to motor generators in the substations. The generators in the substations generate on this particular line 1100 volts, direct-current.

Upon the d-c. bus is connected a Tudor type 484-cell 1000-ampere-hr. battery which floats upon the system as any other standard battery.

There is nothing remarkable or special about this installation as a unit. The battery is standard in every respect, except the battery room, where the floors and wall are insulated from the building.

Even on a three-wire installation, having as potentials 650 and 1100 volts, there is no difficulty experienced from the battery. The only special auxiliary in this double-voltage equipment is the counter-e.m.f. booster regulator. This set consists of a 600-volt d-c. motor and six generators mounted upon the same shaft. The operation of this set is however standard. Each three generators taking care of one side of the system. The voltage regulation of the booster regulator as well as the load distribution between generator and battery is entirely automatic.

Another interesting feature of this Budapest system is the overhead line construction, with its flexible trolley wire suspension, upon the messenger cable. The trolley wire is allowed to slide lengthwise over the tracks, to adjust itself automatically to the climatic variations, allowing a free contraction or expansion of the wire without additional sagging under the suspension clamps, and from which it follows that sparking is almost entirely done away with. Counter-weights of about 3000 lb. at every mile or mile and a half or so about take care of the even trolley tension over their respective sections.

Benjamin F. Wood: I have been connected with a system that has standardization in fact, and lately I have changed to a system that has standardization, to a great extent, in theory. The trolley car man wants everybody to adopt his standard. I noticed in the first picture which was thrown on the screen that there were four or five voltages shown. It does seem that some standardization is desirable, but I think that the electrical man is getting himself into some difficulty with the railroad people when he talks about cost and the little refinements connected with the efficiency of operation. I made some calculations one time on the electrification of a double-track line, 130 miles long, operating 3000 to 3500-ton trains, at twenty minute intervals throughout the day, at a maximum rating of 0.2 per cent, and found that could be done with 600 volts. The difference in cost between the different voltages was comparatively small, only 2 per cent on the total, and the cost of operation would be only a few per cent. When you realize that the total fuel cost on a trunk line is only five or six per cent of the operating expenses, and you have got to sell electric power to the steam railroad at approximately the cost of fuel when you take over that operation by electric service, you will see that when you come to save five per cent, or ten per cent, even, of this fuel percentage, it is of trifling importance when compared with dependability of operation. That is the primary thing. The railroad man wants something he can be sure is going to operate continuously and reliably, and that is the end to which all efforts at standardization should be directed.

Ernest V. Pannell: If I have understood Mr. Renshaw's conclusions correctly, he is strongly in favor of the motor, insulated for 1200 volts and commutating only 600 as opposed to the motor which operates at a terminal pressure of 1200. Now this operation of two motors in series on a 1200-volt trolley has always seemed to me to represent only half a solution of the high-voltage railway problem. It is expedient where a considerable proportion of the running is on the 600-volt trolley but one usually finds that where interurban cars operate within city limits, the switch over from 600 to 1200 volts occurs at the end of the limited speed area so that the motors take up full speed just as soon as full speed is permissible.

The main problems attaching to the design of high-voltage motors are two; those of insulation and commutation. In

constructing a motor which will operate in series with another on 1200 volts, the first problem has to be met. Clearances have to be sufficient to take care of flashover, projections in the interior have to be rounded off and extra slot insulation carried. In a recent instance the slot space factor of a 150-kw., 1200-volt motor worked out at 37.5 per cent whereas the corresponding 600-volt design would probably have a value of 50 per cent; in other words an armature of given size has a capacity 25 per cent lower when insulated for 1200 as compared with 600 volts. Now in making the additional modifications for running the motor direct on 1200 volts the commutator bars have to be increased in number, possibly by 100 per cent and the armature, if a two-turn winding reduced to one turn. Simultaneously however the amperes per motor for a given output are reduced by some 50 per cent this makes it possible to shorten up the commutator by a similar proportion. Although on account of the space required for bearings, fan, etc., it is impossible to add to the core-length every inch saved on the commutator, it will usually be found practicable to increase the core by two to four inches and by this means the armature will carry a greater flux. On the foregoing basis therefore, a motor of given weight will actually have a greater output with 1200 terminal volts than where it is one of a pair designed for working in series on this potential.

As Mr. Renshaw implies, the question of dollars and cents will ultimately settle the maximum voltages for railway operation. We do not run our trains at ninety miles an hour because the cost of track maintenance and power for operation would be prohibitive. Similarly an economical maximum voltage will be evolved beyond which the extra cost and maintenance of the equipment will outbalance the economy on the line copper. Because 1500 volts is about the maximum which can be applied to a railway motor commutator in service with reasonably satisfactory results I would set the maximum desirable trolley pressure at 3000 volts in the present stage of the art.

A. H. Armstrong: There are two rather positive statements made in Mr. Renshaw's paper and to bring them freshly to mind I will quote. With reference to the use of 2400 volts the author states "From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking." On the next page the author goes on to state, "For heavy traction on the other hand this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, does not do so completely." The author then goes on to make the suggestion that 5000 volts direct current be adopted and standardized as the proper d-c. voltage for electrification work.

A number of years ago on the floor of this Institute the suggestion was made to standardize the 15-cycle a-c. single-phase motor system as the standard equipment for steam railway electrifications. At that time not a single 15-cycle a-c. motor was in operation in this country, and but one installation has been made in the many years which have since passed. To-night we have the suggestion that 5000 volts direct current be standardized although there is only one experimental car equipped with 5000-volt d-c. apparatus which has been in intermittent experimental service for a period of a few months.

There are in operation in this country three very extensive railway systems using d-c. motor equipments of 2400 to 3000 volts, and contracts have been let for similar apparatus for two other installations also of some magnitude. In view of these facts it therefore seems pertinent to approach the proposal to standardize 5000-volt d-c. apparatus by asking two questions.

1. What facts are behind the two statements made by Mr. Renshaw in which he broadly discredits 2400 and 3000-volt apparatus as being applicable to main line electrification?

2. What experience is behind the suggestion that 5000 volts be adopted as a standard d-c. potential and what advantages does it offer?

The sweeping statements that 2400 and 3000 volts direct current "are much too low to solve the problem," cannot be accepted without advancing sufficient facts to disprove the economic fitness of the apparatus now operating successfully on three railways and under construction for two more. Especially is this so when one electrification at 3000 volts has a route mileage greater than the combined length of all the electrification thus far completed in this country to date. It is therefore impossible to let go unchallenged the broad statement that potentials considerably higher than 3000 volts direct current must be resorted to in order "to attract the investment of capital in electrification." In the absence of any facts supporting the claim that 3000-volt d-c. locomotives cannot successfully meet the requirements of heavy traction service, it is not out of place to refer to some of the fundamental features of the C. M. and S. P. electrification operating at that potential.

This electrification extends over four steam engine divisions, a total of 440 route miles across three mountain ranges, the Belt, Rocky and Bitter Root mountains, and presents all the problems confronting operation over a broken profile from level track to long sustained grades of 2 per cent. This 440 miles of track is fed from 14 motor-generator substations having an aggregate installed capacity of 59,500 kw. full-load rating. In each of these substations there is one motor-generator set serving as a complete spare so that in normal operation of the road the aggregate substation capacity running is limited to 33,000 kw. The total d-c. load on the 14 substations will probably be less than 14,000 kw., giving a load factor of over 40

per cent of the aggregate running capacity of the substations. This remarkably high load factor is secured by spacing the substations some 32 miles apart as permitted by trolley distribution at 3000 volts direct current. This substation spacing is obtained in most cases with only one 500,000-circular mil feeder reinforcing the two 4/0 contact trolley wires, the exceptions being the 2 per cent grade over the Rocky Mountains and the 1.7 per cent grade over the Bitter Root Mountains, in which locations 1,400,000-circular mil and 1,000,000-circular mil feeder cables respectively reinforce the trolley.

We have then in the St. Paul electrification a good example of what can be done with 3000-volt trolley distribution and the above statement gives evidence that substation spacing is approximately 32 miles, the feeder copper installed is entirely reasonable and furthermore the load factor of the motor generator sets running in the substations under normal service is very good indeed. Furthermore, the 33,000 kw. running in the 14 substations furnish power to 42 main line locomotives and 2 switch engines having a combined continuous rating of 127,000 h.p. or 95,000 kw. which is further proof that the substation spacing is sufficiently great to profit to a large extent in the matter of diversity factor of the several locomotives operating and assigned to each division. A statement of the Butte, Anaconda and Pacific Railway operating at 2400 volts direct current would add further facts to those cited in the case of the C. M. and S. P. and these facts are submitted as substantial evidence that 2400 and 3000-volt direct current are sufficiently high to adequately take care of the demands of main trunk line electrification. The train weight on the St. Paul totals 3500 tons gross including locomotives, and these heavy trains operate against a 2 per cent grade at 15 miles per hour. On the Butte, Anaconda and Pacific trains of 5000 tons gross are being operated against a lesser gradient and the average drop in trolley feeders and ground return on either road will be found to be less than 10 per cent under the average traffic demands and possibly 20 per cent maximum under certain conditions of operation.

It may seem attractive to always consider the use of still higher voltages, but it must be recognized that very high voltages impose their burden of expense and complications upon the motive power and substation apparatus until a point is reached where these costs become so excessive as to more than offset the reduction in feeder copper and other advantages of a high distributing voltage. There is nothing inherently inexpensive in a high-voltage locomotive and there is little saving in the first cost of the entire installation by transferring a certain portion of the initial investment in copper to a corresponding increase in the cost of locomotives which is the result of going to higher potentials.

Referring again to the proposal to standardize 5000 volts direct current, I do not share with Mr. Renshaw the conclusion

that this potential is a natural selection or in any way represents the last word in the development of d-c. locomotive equipments Before the decision was made to adopt 3000-volt d-c. apparatus for the C. M. and S. P., exhaustive experiments were carried out at Schenectady with d-c. apparatus operating as high as 6000 volts with an idea of determining if possible the limiting potential of d-c. apparatus. No such limits were discovered, as with the hastily constructed apparatus tested, it was found possible to successfully open 6000 volts on contactors, circuit breakers and fuses assembled for the purpose and furthermore the current used was obtained from motor-generator sets and was of sufficient volume to demonstrate the successful operation of d-c. apparatus at this potential in commercial service. To my mind therefore it is not a question of the feasibility of operating d-c. equipment at higher than 3000 volts, but rather what advantage either in first cost, cost of operation or increased facilities does the adoption of a higher potential offer.

The 5000-volt car fed from a mercury rectifier tube referred to by Mr. Renshaw constitutes a most interesting experiment but in no way forms a sufficiently solid basis for a recommendation to adopt 5000 volts direct current for heavy traction electrification. If facts can be disclosed which will discredit 2400 and 3000 volts direct current then it will be time to consider the initial installation of d-c. apparatus at a higher potential, and its successful performance perhaps in time may lead to the adoption of a general standard d-c. potential higher than 3000 volts. With the facts at hand, however, I see no reason to go to a higher potential than 3000 volts even to meet the requirements of the heaviest kind of trunk line service. In fact there is much more reason to suggest standardizing this potential with the weight of experience behind it than to blindly adopt a higher potential not yet in commercial service on any scale commensurate with the problems to be solved.

Selby Haar (by letter): I should like to have Mr. Renshaw give his reasons for preferring 5000 volts as the standard. Viewed as a multiple of 1200 and 2400 volts it should, apparently, suit him less than 6000 volts, which is derived from 1500 and 3000 volts. Furthermore I do not see that it is obtained by rectification of a-c. voltage or potential any more conveniently than some other potential of the same order of magnitude.

Carl Schwartz (by letter): Mr. Renshaw's paper in calling attention to the successful application for railway operation of direct current of sufficient voltage to compare in ecomony of transmission favorably with single-phase alternating current suggests a potential of 5000 volts as a standard operating voltage.

Without desiring in any way to detract from the value of standardization, I would like to caution against prematurely adopting a standard high d-c. voltage for railway work.

We have in operation a variety of systems with different pressures so that the ultimate loss on account of lack of stand-

ardization should not be materially increased if standardization was deferred until we are able to foresee more definitely what the future will bring us in new developments and experience.

Practically all standards are the result of gradual development to a degree where a further increase in perfection or efficiency is either impossible or unnecessary and it seems questionable whether we have reached this point as far as voltage for electric train operation is concerned. Standardization if adopted too early either means a check in progress or if progress is not stopped standardization automatically fails.

The paper further permits the conclusion that if high-voltage direct current is as successful as it promises to be, the future standard system, if such a thing is possible, has increased chances to be direct current rather than single-phase alternating current.

The writer has refrained from taking part in discussions concerning the relative merits of single-phase alternating current as compared with direct current for electric traction. There is one feature in his mind, however, for many years and that is the difficulties connected with the generation of single-phase alternating current. These difficulties are usually reflected by appreciably higher cost of current and greater chance of disturbances in the generating station.

If these difficulties can be eliminated by the use of direct current, still retaining essentially the advantages of single-phase a-c. transmission, a long step in advance will be made.

The principal reason for the relatively limited electrification of steam railroads is not that steam railroad men have failed to appreciate the advantages of electric operation but rather the fact that so far the investment required for all of the electric traction systems has been so high that it was in most cases hopeless to expect a saving in operating expenses to pay for the additional fixed charges.

Mr. Renshaw's paper indicates that this handicap shows signs of becoming materially reduced.

N. W. Storer: The point in Mr. Renshaw's paper that should appeal most to the railway engineer is the portrayal of the great progress that has been made in the car and locomotive equipments for operation on increasingly high d-c. voltages, culminating in the 5000-volt car equipment that has been in operation during the past year at Jackson, Mich. The operation of this equipment has been a revelation to all concerned and it may be interesting to discuss briefly the main points of interest in it, even though it has been partially described in the technical papers.

The development of this equipment was carried out in pursuance of a settled determination to find, if possible, a limit to d-c. voltage for railway purposes, or at least to see if it is possible to arrive at one which would be high enough to meet the requirements of heavy electric traction in extreme instances, and

to do this economically. The development of 5000-volt apparatus was started several years ago at a time when 2400 volts was the maximum d-c. potential that had been installed on any line in this country. It was known that an experimental line was in operation in England at 3500 volts, d-c., but no information concerning it was available at that time. Since then, I have had the pleasure of riding on this 3500-volt car and have inspected the equipment. Owing to limitations in the substation generator, the equipment has been operated most of the time with the motors all in series giving half voltage and half speed. However, the commutation of these motors was excellent at full voltage and practically no trouble had been experienced with any part of the equipment, except the dynamotor which was used for furnishing power for lights, control and compressor.

This experience corresponds closely with that of the 5000-volt equipment, except that the latter has no dynamotor.

Any system of electrification, or any voltage that is applied to the electrification of a heavy traction line, should be suitable not only for locomotives, but for multiple unit cars as well. Since the 5000-volt equipment, which has been in operation, consists of four motors of only 100 h. p. each, this can be safely said to be suitable for multiple-unit car operation. In view of the fact that many of the limitations to the voltage of a small motor are much greater than in a large motor, it would appear that it would be still easier to build larger equipments and locomotives, at least the problems of insulation and commutation should be easier.

From Mr. Armstrong's discussion, it may be inferred that he thinks this is a freak construction. Certainly, the designs of the motor and switch groups are quite different from the ordinary types of motors and switch groups for car purposes. However, a careful examination of the equipment will show that the principles are identical with those of the standard well-known types and that the difference is in appearance only; the voltage between commutator bars is no higher than on the ordinary 600-volt motors; the voltages between the upper and lower layers of the armature winding are no greater than with any 1200-volt armature; the number of field coils is less than on the ordinary four-pole moter; in fact, throughout practically the entire motor, the construction is simpler than that of the ordinary 600-volt motor. Practically all that has to be given special care is the insulation of the armature windings from ground. How well this was done may be inferred from the fact that after the car had run over 30,000 miles, one of the armature leads, leading from the coil to the commutator bar, broke off and a hole about $1\frac{1}{2}$ inches in diameter was burned through the armature hood. This armature stood a test of 12,000 volts a-c. to ground without a sign of distress. The commutation has been as near perfect as that of any 600-volt motor, and while there have been cases

of flashing in the motor, they have, without exception, been due to abnormal causes, such as reversed commutating fields or broken brush-holder cable, and in no case has there been any damage resulting from this.

The operation of the switches with the arc splitters has been so successful that there appears to be no difficulty whatever in designing switches to handle any reasonable amount of power at this voltage. The arc splitters serve to greatly increase the length of the arc, as well as to chill it. The insulation of the switch group was so perfect that although the switch group frames were grounded to the car structure, there was no case of a breakdown in the insulation until after a 44,000-volt transmission line had dropped on the trolley wire. Then a short time later, one switch insulator and one motor armature were grounded.

The auxiliaries are very well taken care of by the storage battery, which is connected between the main motors and rail. Since the operation of the compressor is delayed until the car starts, the battery is not required to furnish very much of the power for the compressor motor which operates from the current through the main motors. The battery absorbs the excess or furnishes any current that is required above the main motor current. The duty on the storage battery is, therefore, very light. Test on this equipment shows beyond question the possibility of operating satisfactorily with 5000 volts in light service. There would appear to be no reason to doubt that it will operate at least as well in heavy service.

As to the question of standardization, I do not think that we need to feel that Mr. Renshaw had any intention whatever of starting out to show that 5000 volts could be at once adopted as a standard. It is a point to aim at, and it certainly seems more logical to undertake the development of apparatus for a voltage which it is recognized would be high enough to handle any kind of traffic with a very economical distribution system, than to proceed by the small steps which have thus far been made. As a matter of fact, it is recognized that 5000 volts would not be at all suitable for standardization if it could not be made thoroughly reliable. It has not, of course, yet received a test under conditions which would warrant adopting it for general use, or to replace other established systems, but it is certain that a new "bogie" has been established, and it is a voltage beyond which it appears scarcely worth while at this time to go. To be sure, this same equipment was operated at as high as 7000 volts experimentally with entire satisfaction, but this simply shows the factor of safety which the present equipment has.

There has been some doubt expressed by several of the speakers as to the economy of any higher voltage than 3000. The answer to this question depends solely on the cost of substations and locomotives. If the increase in the cost of locomotives is

going to be a large percentage of the cost of 3000-volt locomotives, the limit would be very soon reached, but this depends entirely on the type of locomotive that is adopted, and the use of the twin-armature bi-polar motor places a very different light on this question of cost from what would appear with the older forms of motors. As a matter of fact, it appears that the additional cost of a locomotive designed for 5000 volts over that for 3000 volts will be a very small percentage of the total cost, while the decrease in the cost of substation and feeder copper will be a very considerable proportion. It, therefore, seems inevitable that a higher voltage than 3000 will be utilized in the near future, and whether this voltage will be 5000, 4200 or 6000, is, to a certain extent, immaterial.

The advantage of a standard which can be adopted by universal consent is so great that I feel that every effort should be made to reach one at the earliest possible date. If we can get together and decide on something which we feel will be proper and fundamental, as Mr. Townley has expressed it, we will be doing far better than by trying so many steps along the line.

In a paper which I recently presented in England, I stated that in a country where there is an autocratic government, one man can decide on what is going to be the standard. In another country, where there is absolute independence and individual initiative, there may be a hundred different things proposed and used to accomplish the same purpose. In the first case while the man may not decide on the best system, it would probably nevertheless operate more satisfactorily than in the latter case where there are so many different schemes, because the cost of manufacture in the first case will be very much less and everyone will become familiar with the one system and kind of apparatus, and the operation will undoubtedly become satisfactory even though there may be some other system which would have been a little cheaper under the same conditions. At present, we are required to design apparatus to meet many different systems which are really intended to perform the same work. In this way, the cost of development and manufacture runs up to an enormous figure, which the operating companies must eventually pay for.

Mr. Sprague has, as usual, given a spicy addition to the discussion of the paper, although one must search a long time before finding wherein it applies to the subject under discussion. It would appear that he assumes from the fact that Mr. Renshaw, who represents the company which has been responsible for practically all of the successful single-phase installations in this country, has presented a paper outlining the possibilities of high-voltage d-c. apparatus, that the single-phase system is, therefore, dead. A little further investigation of the question will prove to Mr. Sprague's satisfaction that the single-phase system is very much alive.

Mr. Sprague has quoted one of my previous statements in regard to the influence of cost on the system of electrification.

I still hold that the ultimate decision will be based on the first cost and the cost of operation, provided the systems are equally reliable. It is certain that reliability is going to be a prime factor, but reliability is a relative term. There are many things on a railroad which cause delays to traffic. If the number of delays incident to matters entirely apart from the power system is very large in comparison with the number due to the electrical equipment, the question of reliability of the latter becomes of less importance. 600-volt apparatus would doubtless be more reliable than any of the so-called high-voltage or single-phase systems, but the value of the small additional reliability would be far less than the extra cost of electrifying a long line with this voltage.

C. Renshaw: Mr. Sprague's principal point of disagreement, if I understand him rightly is that my simile was somewhat overdrawn, when I asserted that it was practically a universal belief, ten years ago, that 600 volts was the maximum d-c. railway potential, since even at that time he had predicted some of the things which have now come to pass. Aside from this minor point, however, I judge from his remarks that he agrees substantially with the ideas I have expressed.

Mr. Davis points out that with a given train unit the problem of distribution is simplified as the number of tracks increase. A certain minimum size of trolley wire must be used over each track for mechanical strength and with two or three or four tracks, the combined conductivity of the several trolley wires a ndof the various rails in parallel necessitates a less amount of auxiliary feeder than if only a single track were electrified. Stated in another way, with a fixed amount of auxiliary feeder, the greater the number of tracks the lower the voltage which can be used with a given economy of distribution.

While it might be inferred from Mr. Davis's remarks that in view of these facts, he would advocate selecting the voltage for any given electrification according to such circumstances and thus perhaps using 1200 volts in one case, 1500 volts in the next, 2400 volts in a third, 3000 volts in a fourth, etc., I believe that he merely wished to call attention to the principle rather than to advocate such a multiplicity of voltages for future heavy electrifications.

Mr. Davis states also, that since motor-generator sets and synchronous converters are usually designed to stand three times normal load for short periods, there will be no saving in the total amount of substation apparatus by increasing the load factor beyond 33 per cent. This analysis, however, overlooks the fact that the machines which have been designed to stand three times normal load have been made in this way to suit the loads which they must carry and not because such designs give the most desirable or the least expensive machines.

Finally, Mr. Davis states that as a rule the cost of the locomotives for any given electrification will approximate one-third

of the total cost and that if there is a material increase in the cost per locomotive for a higher voltage as compared with a lower one, this increase might prove the determining factor. This fact is so obviously true that I thought it unnecessary to mention it. The cost of equipments for 1200 volts, however, is but little more than that of similar ones for 600 volts. Presumably, also, the cost of locomotives for 3000 volts has not proved materially greater than that of equivalent ones for 2400 volts. It seems probable from careful estimates that in view of the improved types of construction that are available, locomotives for 5000 volts can be built so as to cost but little more than if made for 3000 volts, and all of the statements in the paper with regard to the use of 5000 volts have been based upon this idea.

Mr. Potter agrees that my comments on the unfortunate circumstances that have given us electrifications at *both* 2400 and 3000 volts are in the main well taken, and this broad-minded position on the part of a man of Mr. Potter's ability and attainments is the most hopeful sign in the entire discussion. With this point appreciated, everyone must surely see the desirability in future of avoiding similar multiplications of voltages as far as possible, and as it was to point out this fact that the paper was primarily written, I feel decidedly encouraged by this statement from Mr. Potter.

Mr. Potter suggests a change in the last sentence of the paper where I said that if 5000-volt apparatus were "commercially available" such and such would be the case. He suggests the words "commercially economic," instead of commercially available. Such a change, however, would not in any way affect the meaning which I intended the sentence to convey, for to my mind, the apparatus which is out of line in cost, is not commercially available.

Another portion of Mr. Potter's remarks which appealed particularly to me was that in regard to the collection of current. After saying that this had seemed to be a great problem and that some years of study had been given to it, he adds "The solution was found to be rather simpler than anticipated." This sentence appealed to me because I believe that some day I will have the pleasure of hearing Mr. Potter, and some of the other gentlemen who have commented upon the paper, use these same words in regard to the employment of apparatus for 5000-volt direct current and the standardization of voltages for heavy electric traction.

Mr. Townley agrees that a potential of 3000 volts is not high enough to hold the field of heavy electric traction, but he is not sure that even 5000 volts will do this. He announces, also, that he is against standardization, seemingly because he believes standardization tends to discourage advances in the art.

With regard to the last idea it seems to me that just the opposite is true. Nothing tends to encourage the development of

an industry so much as a semi-permanence and general interchangeability of the apparatus for carrying it on, and no class of apparatus can be really developed on a commercial basis unless its use for a reasonable term of years is assured. I believe therefore that it would be much more encouraging to the art of heavy electric railroading if, instead of employing a little higher voltage in each successive case, where d-c. apparatus is used, some definite voltage, sufficiently high to meet all reasonable requirements, was generally recognized as being standard.

Replying to Mr. Oesterreicher, I had not mentioned storage batteries in connection with high-voltage d-c. roads, since as far as I know it has never as yet been necessary to consider their use seriously on such roads in America. I see no reason, however, why batteries could not be arranged for 5000-volt direct current if this was necessary.

Mr. Wood has made a good point by indicating that it is not so much the *cost* of electrical apparatus as its *worth* which concerns the railroad man, since the cost of the electrical part of the system is a comparatively small part of the total. "The railroad man", he says, "wants something he can be sure is going to operate continuously and reliably and that is the end to which all efforts at standardization should be directed."

It is obvious that if the skill of the various available designers can be constantly applied to perfecting the details of any given apparatus, rather than to changing its fundamental character, the results Mr. Wood is looking for are more likely to be secured. If the railroad man, also, is offered something that is already in use he can be much more certain of the results he will obtain. I believe Mr. Wood's remarks therefore are strongly in favor of the policy I have been advocating, of choosing the right thing for any given class of work as quickly as possible and then sticking to it.

Mr. Pannell, in advocating the use of motors wound directly for 1200 volts rather than of two 600-volt motors in series, in cases where the cars are not required to run at full speed on 600 volts over part of their route, has overlooked one important fact. Where a manufacturer builds motors for operating on 600 volts, as well as for 1200 volts, a considerable investment in drawings, patterns, tools, etc., can be saved by the use of the same motors with minor changes for the two voltages, instead of radically different designs. In arguing that 1500 volts is about the maximum potential which can be applied to a railway motor commutator in service and that to allow not more than two motors in series he would therefore set the maximum trolley potential at 3000 volts, he has apparently forgotten the double armature motor which Mr. Storer described and which with 1500 volts per commutator and two motors in series would permit a trolley voltage of 6000.

Mr. Haar inquires why the particular voltage of 5000 was chosen, since it is not a direct multiple of 600, 1200, or 1500.

In undertaking to produce d-c. apparatus for a voltage high enough to be suitable as a standard for a reasonable period of years, we started to design our apparatus for 4800 volts, or double the value of 2400 volts, then the maximum contemplated. This was later raised to 5000, however, since it had a more euphonious sound than 4800. As a matter of fact our experimental line has been operated at about 5300 volts and the apparatus was tried on the test track with voltages up to 7000.

I am not particularly concerned with the exact value of the voltage chosen, whether this be called 4800, 5000, 5500, or 6000, since by the term "5000 volts" in the paper, I have intended to include anything in this range. The fundamental point which I have been trying to make, is that *some* voltage in the neighborhood of 5000 should be generally recognized as a standard for heavy electric traction so that d-c. electrifications can be installed with some degree of uniformity, instead of on a basis which will give each one a voltage just enough higher than its predecessor to be different without being sufficiently high to be adhered to in the next case.

Mr. Schwartz is apparently possessed by the same fear which Mr. Townley has expressed, that standardization tends to limit progress. I believe I have covered his points sufficiently in replying to Mr. Townley's remarks.

In referring to the discussion presented by Mr. Armstrong the first thing to be done is to free oneself from the confusion created by his way of grouping 2400 and 3000 volts together as though they were one and the same, instead of being different systems, sufficiently far apart to be entirely distinct and yet so close together that, as emphasized by Mr. Potter, it is unfortunate that we have both of them. Taking up his question, then, as to what has discredited these two systems for heavy electric traction, I would reply that as far as the 2400-volt system is concerned, Mr. Armstrong himself discredited it by ruthlessly abandoning it in favor of 3000 volts when the first real railroad was presented to him for electrification.

As to the 3000-volt system, nothing has as yet "discredited" it. The St. Paul electrification at 3000 volts is a magnificent piece of work, but so is the New York Central electrification at 650 volts, and there is no more reason to suppose now that the former represents the magic limit of voltage for minimum cost than there was a few years ago to suppose the same thing about the New York Central. I believe, in fact, that if Mr. Sprague would hunt up the bibliography with even a small part of the assiduity he has used in preparing his discussion, he could show that only a few years ago Mr. Armstrong himself was just as positive that the 650-volt system was the only rational way to electrify a railroad, as he now is that there is no possible reason for using more than 3000 volts. I have great hopes, therefore, that Mr. Armstrong will keep on raising his voltage and that if we give him sufficient time, it will sooner or later reach 5000. I will hence waste no effort in trying to convince him now.

While it is true that the operation of one 400-h. p. car for 35,000 miles constitutes the sole commercial experience with 5000-volt direct current, this is a much greater experience than was available when the first line was built to operate at a voltage of 1200 instead of 600, or when the first electrification was undertaken using 2400 volts instead of 1200. From this standpoint, therefore, the matter seems in reasonably good shape.

"It may seem attractive", says Mr. Armstrong, "to always consider the use of still higher voltages" but to me it decidedly does not seem attractive and it is in the effort to set others thinking of the obvious disadvantage of such a procedure that all of my energies have been directed. In the period referred to in the beginning of the paper, 600 volts was the established standard for electric railways, so that "an electric railway" meant a 600-volt d-c. electric railway. This particular standardization on 600-volt direct current, was not brought about by action of the A. I. E. E., or any similar body, but by general recognition of the merits of the case by manufacturers and users of the apparatus. It was nevertheless very effective. When it was proposed to build or equip a given line in those days there was no question as to voltage, or system, to confuse the main issue of whether the work should or should not be undertaken, and it was during this period that most of our present city and interurban railways were built.

To establish the same conditions in the field of heavy traction at this time, is of course a much more difficult matter, but there is no question that the advantage to all concerned would be equally great could this be done. It is not my idea that such a standardization could be brought about by any resolution or recommendation of the Institute, and in suggesting the adoption of a standard I had no such action in mind. If standardization comes, it must be by a general consensus of opinion, as in the case of 600 volts, and my real object has been to start such an idea.

Most of the speakers who took part in the discussion seem to have allowed themselves to be misled by the difficulty of the problem. Not seeing any way to bring about such a standardization of voltage immediately, they have felt forced to speak against the necessity or the desirability of it. No great work is ever accomplished, however, without a great deal of thought and planning and dreaming long in advance of the realization, and if I have succeeded in starting some of this thought or planning or dreaming, I will feel that the first steps have been taken.

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ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWERS

BY LAWRENCE ADDICKS

ABSTRACT OF PAPER

The electrochemical industries have grown to be of great value to this country; they have a fundamental interest in the development of cheap power; they offer nearly ideal power loads of magnitude; they must be located strategically as regards supplies and markets; Niagara power is not cheap enough nor is it sufficient in its present state of development to afford growth to these industries; the industries have so far been hardly strong enough to develop large powers themselves; great expansion should follow the development of cheaper power in accessible locations; and the country is vitally interested in the development of the nitrate industry, which must have very cheap power in great quantity in order to exist. In view of all these considerations, a liberal water power policy on the part of the government would seem to be a step in the right direction.

THE INDUSTRIAL processes founded upon electrochemistry have a part in the manufacture of a very wide range of commercial products. By definition they all require electric power in greater or less quantity and in many instances power is a large item in the cost sheet. The power requirements vary enormously, however, in different cases, and many other considerations enter into the determination whether a given industry can flourish in a given location. It is the purpose of this paper to point out briefly the interrelation of some of these factors and the interest the industries have in the development of cheap power.

The electric current may be used for its chemical effect, giving oxidation products at the anode and reduction products at the cathode in an electrolytic cell; or it may be used for its heat effect in an electric furnace, where high temperatures and a controlled atmosphere are desirable; or both effects may be utilized, as in the electrolysis of fused salts. Finally, we have the effects of electric discharges through gases.

It is not generally appreciated to what extent electrochemical processes have entered into some phase, at least, of nearly every branch of our industrial life. A small beginning in electro-

plating two generations ago has developed until the great majority of the copper output of the world is electrolytically refined; silver is thus parted from gold, and gold from the platinum metals, bismuth-bearing lead can be successfully treated, electrolytic nickel is well known, and zinc and tin so refined are appearing in the market. In general, electrolytic refining not only increases the purity of the metal but makes possible the recovery of the impurities as byproducts, thus greatly cheapening the cost of some of the less common elements.

The electrolysis of common salt is the basis of the electrolytic alkali industry, the products of which are caustic soda, the starting point for various chemical industries, and used in very large quantities in soap making, mercerizing cotton, etc.; metallic sodium, also used as a foundation for other products, such as the cyanide so largely used in the metallurgy of silver and gold; chlorates, used in the manufacture of matches, certain explosives, etc.; hypochlorites, of value for bleaching; chlorine, employed as a sterilizing and chloridizing agent and for the formation of bleach.

The electric furnace has created a host of new industries. Very briefly, the chief products consist of abrasives, such as carborundum, alundum, aloxite, etc.; graphite; silicon; ferro-alloys, such as ferro-silicon, -manganese, -chrome, -tungsten, -vanadium and others, which are used in the steel industry for producing sound ingots, hardening, making special steels, high-speed tool steel, armor plate, etc.; refined steel of crucible grade; phosphorus by distillation; calcium carbide, used in the generation of acetylene and in the manufacture of cyanimid; and so on. It is also being tried out experimentally as a competitor of the combustion furnace in the metallurgy of many metals. Used as an electrolytic furnace, we have the very important application to the production of aluminum.

The industrial use of electric discharges through gases is still in its infancy, but we have ozone and nitric acid among the products, the former used for sterilization and the latter as a base for fertilizers and explosives.

This brief review of electrochemical products is by no means exhaustive. If it were followed to a logical conclusion and a list made of all the uses of all the products it would be a formidable affair, but I think enough has been said to establish the first point that I wished to make, namely, that electrochemistry today plays a large part in our industrial life and that its industries are more important than the public at large realizes.

Now every one of these industries consumes large quantities of energy. Starting at the bottom, we have the refining of lead at 120 kw-hr. per ton, and of copper at 300 kw-hr. per ton. Where diaphragms are used, as in nickel refining, the power rises to about 3000 kw-hr. per ton. Where insoluble anodes are used for the recovery of a metal from solution, the power will range from 700 to 4000 kw-hr. per ton, depending upon the metal, the amount of depolarization at the anode, and of course the current density.

Turning now to electric furnaces, an ordinary melting operation, such as casting an alloy or refining steel, generally requires from 600 to 1000 kw-hr. per ton. In the production of ferro-alloys, which is really a smelting operation, a large amount of energy is consumed by the endothermic reaction, and the power used runs from 3000 to 8000 kw-hr. per ton of product, depending upon the grade of alloy made. The aluminum furnace requires 25,000 kw-hr. per ton of product. The electrolytic refining, alkali and aluminum industries require direct current; the graphite, carborundum, melting and ferro-alloy furnaces use alternating current. In general low voltage and high amperage is employed. In the case of alternating current this is readily obtained by the use of suitable transforming units; in the direct-current processes it is customary to connect a sufficient number of cells or furnaces together to obtain a reasonable line voltage. Individual industries in plants of modern commercial size require blocks of energy ranging from 5000 to 50,000 kw., and it is self-evident that the charge for energy in such quantities is a vital item in the cost sheet. And this brings us to the question of what is cheap power.

Twenty years ago Niagara power was cheap, but in the meantime steam power has made such strides that Niagara and similar water power developments can no longer be considered the exclusive sources of electrolytic power. In so speaking I am of course not considering the very low rates which were made on a few contracts in the early days at Niagara, but of the present rate of about 0.3 cent per kw-hr. ($20 a horse power-year). With the very high economy of the large turbo-alternator it is quite possible to meet this figure by locating a plant near some of the coal fields. It is therefore idle to discuss any new source of power higher in cost than Niagara.

It is often suggested that electrolytic plants could be operated to advantage on off-peak power. This is seldom practical. In the first place, to shut the power off for several hours in many

cases creates very undesirable chemical conditions; then, in most electric furnace processes there is a loss of heat while standing which calls for the expenditure of excess energy upon starting up; and finally, there is the loss of production due to several hours' idleness to be reckoned with, and in this connection it must be remembered that electrolytic plants generally call for heavy investments, the fixed charges on which need every possible ton to divide by. After these handicaps are properly allowed for, it is only in exceptional cases that a mutually satisfactory contract can be made.

And then we have the power contract to deal with. The owner of the water power generally requires that a fixed minimum annual sum shall be paid regardless of consumption. This is naturally a little hard on periods of low output. On the other hand, excess power is apt to be either subject to prior sale or charged at an excess rate, so that the manufacturer has to balance his output on the tip of his nose, so to speak, if he is going to realize the advertised rate per kilowatt-hour.

Next, we have the difficulty that the power is invariably sold as high-tension alternating current, which imposes various conduction and conversion losses on the purchaser which may easily absorb 15 per cent of the incoming power. The transformers and other apparatus represent a considerable investment, shattering another illusion—that the "other fellow" had to put up all the money. Then in some contracts we mustn't unbalance the phases or let the power factor run off.

By the time all these allowances are made, the power originally spoken of as 0.3 cent per kw-hr. is nearer 0.4 cent, plus a considerable investment, a figure which begins to approach the cost of steam power in the vicinity of New York City, using buckwheat coal; and, as before stated, Niagara Falls is no longer bargain power. This statement leads to a number of questions about as follows:

(1) If cost of power is the great consideration, and Niagara Falls has no longer the cheapest power, why do all the electrochemical industries remain grouped there?

(2) If electrochemical industries have been able to thrive on present power costs, is not the cry for cheaper power merely one for additional profits?

(3) We have in this country a variety of fuel supplies: why are not great central stations established in some of these fields if the resulting power would cost less than water power?

In endeavoring to answer some of these questions, I hope to

bring out the main factors which have to be considered in establishing an electrochemical industry.

As to the first question, the cost of power, while important, is by no means the whole, and often not even the controlling, factor and Niagara, while an electrochemical center, is not the sole residence of such industries. There are three main factors to be considered in locating such an industry; transportation, labor and power; and in reality power may be placed under the transportation heading, leaving but two. In any industry, raw materials must be carried to the manufactory and the finished products to their markets. As fuel can be carried and electric current can be transmitted, it is evident that the increased cost of power due to such movements is simply a freight item. The moment this is realized the problem does not differ from that presented by any other manufacturing operation. Where raw materials are bulky and the product and power used are not, the work will be carried on near the source of the raw material, as in the case of a plant for reducing copper from its ores. Where power or fuel is bulky it may become the controlling factor. In zinc metallurgy, for example, the ores are rich and it takes three tons of coal to smelt one ton of zinc. Zinc smelters are therefore located in the fuel belts. An electrochemical instance is aluminum. Here the ore is carried great distances in order to avoid the transmission of 25,000 kw-hr. per ton of aluminum produced. Then again, the process may not greatly change the bulk of the raw materials, as in refining operations, but transportation still governs. In electrolytic copper refining the plants are, with a single exception, at tide water. Here the Western smelters bring the product up to 98 per cent copper. There is but little dead weight in transporting this crude copper, and the silver and gold contents if separated at the smelter would have to travel by express. Also labor and power are cheaper at tide water where the market is, than in the Rocky Mountains where the smelters are. The one exception at Great Falls, Montana, is where an exceptionally cheap water power exists at the smelter, precious metal contents are low, and there is the possibility of considering Western markets and movements via the Panama canal. Finally, labor is a large item. If we assume that a man earns \$3.00 a day and that power costs 0.3 cent a kw-hr., the two are of equal importance when an industry uses, on a 24-hour day, 42 kw. per employee. By no means all the electrochemical industries use such a proportionate amount of power. I think enough has been said to

show that an appreciation of geographical values is of the utmost importance and that power is of purely relative value.

If we examine the industries grouped around Niagara Falls, we shall find that practically all of them have been created in the last 25 years; that many of them use as raw materials such things as carbon, salt, silica, etc., which are obtainable within a reasonable distance; and that they are chiefly those electric furnace operations which rate among the larger power consumers in the electrochemical list. Now, the investment called for in electrochemical plants is generally high, and it can be readily understood that it is a very welcome lessening of obligation in starting a new industry to be able to cut out the money which would be tied up in a private power plant. Also, really low costs on steam power can not be obtained until a load of about 15,000 kw. is built up. Then, Niagara Falls is in a strong location as far as transportation facilities are concerned. Water transportation through the Great Lakes is at hand and Buffalo is a railroad center. The labor market is also good.

As to the second question, whether 0.3 cent per kw-hr. is not low enough to allow any electrochemical industry to thrive, it is simply a matter of competition. Useful as electrochemical products have proved, they are not necessary to sustain life; we got along, after a fashion, a quarter of a century ago before most of them were heard of. We must remember, however, that every one of these products has had to win its way against competition. Graphite and the abrasives have had to compete with natural graphite and emery; aluminum had wood and copper to displace; the alkali products can be produced chemically; the ferro-alloys can be made in blast furnaces; electrolytic refining had fire methods to compete with; electric steel refining replaced the crucible method; and so on. It is quite conceivable that power costs should be so high that the older processes in some cases might revive. On the other hand, electrochemical processes are in their infancy and a decrease in the cost of power is bound to stimulate new lines of production. It is quite within the range of possibility that many of the combustion furnaces now used in metallurgy can be some day replaced by one or another type of electric furnace. Hydrometallurgy, which is closely linked with electrodeposition, has also a large field before it. The question of electrical action on gases is a most promising possibility for development. Take the fixation of atmospheric nitrogen, one of the largest technical problems which this nation has to face today. We import large quantities

of Chilean nitrate every year. Our only local sources are decomposing organic matter and a small quantity of byproduct ammonia salts. Nitrogen is a necessary constituent of fertilizer and is the base of all explosives. The military recklessness of being forced to depend upon imported material for the manufacture of ammunition in these troublous times has recently brought this question very much to the front. There are several methods of fixing the nitrogen of the atmosphere in use abroad. Two of these processes, the oxidation of nitrogen in the electric arc and the conversion of calcium carbide into cyanimid, are suitable for commercial development in this country, and in fact there is already a large plant devoted to the cyanimid industry at Niagara Falls, Canada. The arc process requires large quantities of electric power; several hundred-thousand horse power are so used in Norway. The cyanimid process, while chemical, requires calcium carbide, an electric furnace product, as its raw material. As matters stand today it may be necessary for the government to subsidize this industry to guarantee its required supply of explosives in time of war. If we had 500,000 h.p. available at say 0.15 cent a kw-hr., (a common figure in Scandinavia), this great industry would develop at once on a peace basis on account of the fertilizer demands.

As to the third question, our electrochemical industries are either buying from some water power company or they are generating power themselves from steam. The water power company naturally sells its output for all that it will bring, with a weather eye on the local cost of steam, and very few industries are large enough to save this profit by operating their own hydraulic plants. Unfortunately most of our high-head water powers, which are capable of development on a small scale and with moderate investment, are on the Pacific coast where markets do not yet exist for many electrochemical products. Most of the latter are of such a nature that they serve only as raw material in manufacturing operations conducted chiefly on the Atlantic seaboard. The time may come when various electrochemical industries will associate in a cooperative power development. In this case the eastern coal fields will be carefully considered, especially as many of the processes require large quantities of coal for operations entirely apart from electrochemistry, such as evaporating or heating liquors, reverberatory smelting, etc. Near a sufficient and suitable supply of water for boiler feed and condensing, and close to the coal mines, a mammoth steam plant could certainly give a lower power cost than now

obtainable at Niagara. Perhaps the chief objection to such a scheme would be the present unsatisfactory labor situation in the coal fields.

Then we have the various propositions depending on the use of gas. Natural gas is fast disappearing and can no longer be considered for such a plan. The beehive coke oven, which used to be held up as a glaring example of heat waste, is also rapidly giving place to various retort types. The use of producers supplying gas engines begins to lose its attractiveness as the cost of fuel decreases, and placing the steam plant near the colliery deals a heavy blow to this scheme, which offers low fuel consumption as an offset to great first cost and lack of overload capacity. The byproduct coke oven is more attractive, but so far it has been linked up with either the iron and steel industry or the production of illuminating gas, and it is not very desirable to be tied up with another industry and run the danger of being subject to the ups and downs of industrial prosperity in an unrelated field. Then we have our peat deposits, which somehow never seem to receive really serious consideration.

If we knew that there was no hope of getting lower water power costs, I believe some great central power plant would eventually be established. The two stumbling blocks at present in the water power question are government control and the great cost of developing low-head powers. One possible way of meeting the latter difficulty is to consider the value of the development from other points of view, such as irrigation, navigation or flood prevention. All the power plant wants is the potential energy in the water.

Summing up, the electrochemical industries have grown to be of great value to this country; they have a fundamental interest in the development of cheap power; they offer nearly ideal power loads of magnitude; they must be located strategically as regards supplies and markets; Niagara power is not cheap enough nor is it sufficient in its present state of development to afford growth to these industries; the industries have so far been hardly strong enough to develop large powers themselves; great expansion should follow the development of cheaper power in accessible locations; and the country is vitally interested in the development of the nitrate industry, which must have very cheap power in great quantity in order to exist. In view of all these considerations, a liberal water power policy on the part of the government would seem to be a step in the right direction.

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WATER POWER DEVELOPMENT AND THE FOOD PROBLEM

BY ALLERTON S. CUSHMAN

ABSTRACT OF PAPER

The great increase in population of the United States has been chiefly in urban districts while the increase in population in rural districts has been comparatively small. This results in a continuously growing demand for food with a relatively small proportion of our population as food producers. The production of some of our most highly nitrogenous food products has been steadily declining and American farmers have been producing less per acre than European farmers.

The food supply depends in the last analysis upon the plant food supply. The production of nitrogen, which is one of the three principal fertilizer ingredients, is distinctly a water power proposition involving the fixation of atmospheric nitrogen. More than 80 per cent of mixed fertilizers produced in the United States is used east of the Allegheny Mountains, and for the fertilizer problem the water power must be developed in those parts of the country where the demand for intensive agriculture exists. A feasible and proper plan for water power development in this country will have a profound influence on the development and distribution of cheap fertilizer ingredients which are so necessary under modern intensive conditions in the growth of population and its relation to agriculture.

IN OUR centennial year 1876, just forty years ago, Thomas Huxley, the great English scientist, delivered the dedicatory address at the formal opening of the Johns Hopkins University in the City of Baltimore. In the course of this address he gave utterance to the following pregnant words:

To an Englishman landing upon your shores for the first time, traveling for hundreds of miles through strings of great and well-ordered cities, seeing your enormous actual, and almost infinite potential, wealth in all commodities, and in the energy and ability which turn wealth to account, there is something sublime in the vista of the future. Do not suppose that I am pandering to what is commonly understood by national pride. I cannot say that I am in the slightest degree impressed by your bigness, or your material resources, as such. Size is not grandeur, and territory does not make a nation. The great issue, about which hangs a true sublimity, and the terror of over-hanging fate, is what are you going to do with all these things? What is to be the end to which these are to be

the means? You are making a novel experiment in politics on the greatest scale which the world has yet seen. Forty millions at your first centenary, it is reasonably to be expected that, at the second, these states will be occupied by two hundred millions of English-speaking people, spread over an area as large as that of Europe, and with climates and interests as diverse as those of Spain and Scandinavia, England and Russia. You and your descendants have to ascertain whether this great mass will hold together under the forms of a republic, and the despotic reality of universal suffrage; whether state rights will hold out against centralization, without separation; whether centralization will get the better, without actual or disguised monarchy; whether shifting corruption is better than a permanent bureaucracy; and as population thickens in your great cities, and the pressure of want is felt, the gaunt spectre of pauperism will stalk among you, and communism and socialism will claim to be heard. Truly America has a great future before her; great in toil, in care, and in responsibility; great in true glory if she be guided in wisdom and righteousness; great in shame if she fail. I cannot understand why other nations should envy you, or be blind to the fact that it is for the highest interest of mankind that you should succeed."

Thus spake, almost half a century ago, one of the most prescient and philosophic minds that the world has yet produced. Our population has already risen from forty to one hundred million people, and it is our present, as well as our future task, to feed not only our own teeming populations, but also, in some large measure, a war stricken Europe, and, from time to time, a famine stricken Orient. It is well that we should examine our resources and review what we have done or are about to do with our heritage. "What are you going to do with all these things?" "What is to be the end to which these are the means?"

It is not my present intention to inflict upon this audience a multiplicity of statistical data, but some significant figures must be here referred to as an introduction to the points that are to receive special consideration in later paragraphs. In consulting the statistical data, I have purposely confined myself to government publications of date not later than 1914. The great European struggle, breaking out in the fall of that year, rendered all world conditions unstable and artificial, so that statistics of war years may easily be confusing and misleading.

In the annual report of the United States Secretary of Agriculture, for 1914, we learn that although the population of the United States has increased twenty-three million in the past fifteen years, the strictly rural districts have shown an increase of barely six million. More mouths to feed with fewer husbandmen, is perhaps *the* most important problem of our most modern age.

Again, from our conservative Secretary of Agriculture we

learn that: " While there is an increased diversification of agriculture, and both a relative and absolute increase in important products, such as wheat, forage crops, fruits, dairy products and poultry, we have to take note not only of a relative but an absolute decrease in a number of our staple food products such as corn and meats. In the former in the last fifteen years there has been no substantial advance. In cattle, sheep and hogs there has been an actual decline—in cattle, from the census year of 1899 to that of 1909, from 50,000,000 head to 41,000,000; in sheep from 61,000,000 to 52,000,000; in hogs from 63,000,000 to 58,000,000. Since 1909 the tendency has been downward, and yet during the period since 1899, the population has increased over 20,000,000. This situation exists not in a crowded country but in one which with 935,000,000 acres of arable land, has only 400,000,000, or 43 per cent, under cultivation, and in one in which the population per square mile does not exceed 31 and ranges from 0.7 person in Nevada to 508 in Rhode Island. Just what the trouble is no one is as yet sufficiently informed to say. It can scarcely be that the American farmer has not as much intelligence as the farmer of other nations. It is true that the American farmer does not produce as much per acre as the farmer in a number of civilized nations, but production per acre is not the American standard. The standard is the amount of produce for each person engaged in agriculture, and by this test the American farmer appears to be from two to six times as efficient as most of his competitors. Relatively speaking, extensive farming is still economically the sound program in our agriculture, but now it is becoming increasingly apparent that the aim must be, while maintaining supremacy in production for each person, to establish supremacy in production for each acre."

In other words, and I am now speaking for myself, extensive agriculture must ultimately be practised in an intensive manner, if the food supply of an ever-growing population is to be economically produced. I have no desire to take issue with the Secretary of Agriculture in respect to what he has said about the efficiency of the American farmer. We cannot, however, overlook the fact that European farmers are obtaining higher yields per acre on the selfsame soils that supported our own ancestors before their emigration across the seas, perhaps centuries ago, whereas our own agricultural operations began on virgin fields which in too many instances are already run down if not abandoned. If these things are so, lack of efficiency and careless

sense that one cannot go on forever drawing capital from the bank faster than it is put in. We owe our soils at least as much plant food as we take away from them, or agricultural bankruptcy is only a question of time. Agricultural bankruptcy spells ultimate starvation and it spells nothing else.

In 1914 we imported into the United States some 500,000 tons of Chile saltpetre at a value of about $18,000,000. It has been estimated that perhaps one-quarter of this found its way to the soil, in addition to such other forms of fixed nitrogen as ammonium sulphate from coke recovery and the various kinds of organic nitrogen, such as slaughter house and other refuse. But all this is not nearly enough. In Norway alone about 500,000 kilowatts are consumed in the manufacture of artificial saltpetre. In the United States proper it is doubtful if any artificial nitrate has as yet been produced on any scale beyond the experimental, and yet it has been computed that every cubic mile of our atmosphere contains enough raw material in the form of free nitrogen to satisfy our total present consumption for more than half a century. I know of no stronger argument than this for the immediate development of our available water powers, unless it be that these same water powers put to work on nitrogen fertilizers could, at the same time, provide the material necessary for the national defense in case of war.

I should like to take this occasion to add my voice to those of many more distinguished colleagues, in pointing out that though it may be considered desirable to develop water powers in this country, it is very important to take into consideration that such water powers should be suitably located, and that the cost of production of electrical energy should be as low as possible. This is particularly true with respect to the manufacture of artificial fertilizer. The cost of munitions matters little in the face of the emergency of war, but the cost of plant food must of necessity always be kept at a minimum. A water power that costs capital a hundred dollars or more per horse power to develop, and that must be rented for from $17.00 to $20.00 per horse power year, will never solve the problem of cheap food production. Some system for developing low-cost water power must be devised, or, as far as the food problem is concerned, we shall never become self-sustaining or nationally independent. Up to 1914 more than 80 per cent of all the mixed fertilizer produced in the United States

was used east of the Allegheny Mountains. This point is admirably illustrated in the fertilizer expenditures map taken from the Thirteenth Census of the United States, which will be discussed in a later paragraph. A developed water power in Alaska, Washington and Oregon could have no possible influence upon this condition. To be practical, electrical water power must serve its own market and its own neighborhood, or it might as well be located on the moon. The growing city populations composed of the millions who live in such great cities as Boston, New York, Philadelphia, and Baltimore, do not contribute to the production of food. With respect to food, they are consumers only, and the soil alone can feed them. It is inevitable that sooner or later the potential energies of our great water powers must be harnessed to the end that the nitrogen of the air may be fixed to feed the soils.

With respect to the necessary supplies of plant foods other than nitrogen, it has not as yet been seriously considered to utilize electric power, but, speaking to electrical engineers, I can say that the extraction of potash from feldspathic and granitic rocks by electrolysis presents by no means an insoluble or even, in my opinion, a difficult problem. It is perhaps the easiest way that has been as yet proposed to obtain potash artificially, which only awaits cheap enough power to become a reality. I need only remind you that in the silicate rocks of which our mountain ranges are composed, there lie dormant untold billions of tons of potash, to show that when the proper time comes we will not want for raw material. On this special topic I am well informed, for I have made a close study of it in the laboratory and in the field for many years.

In regard to our supplies of phosphate, Nature has been extraordinarily generous to this country, and the vast phosphate fields of the South and West are in no immediate danger of exhaustion. In order to make the phosphoric acid content in these phosphate deposits available for agriculture, it is necessary and usual to treat them with sulphuric acid in the manufacture of super-phosphates. It happens, however, that we possess very large deposits of phosphate rock which, while rich in phosphoric acid, contain also as impurities something more than 5 per cent of iron and alumina. Such phosphate deposits as these cannot be treated by the usual sulphuric acid method, owing to the fact that they show a tendency when treated with the acid to become sticky so that they cannot be ground for mixed fertilizer or be

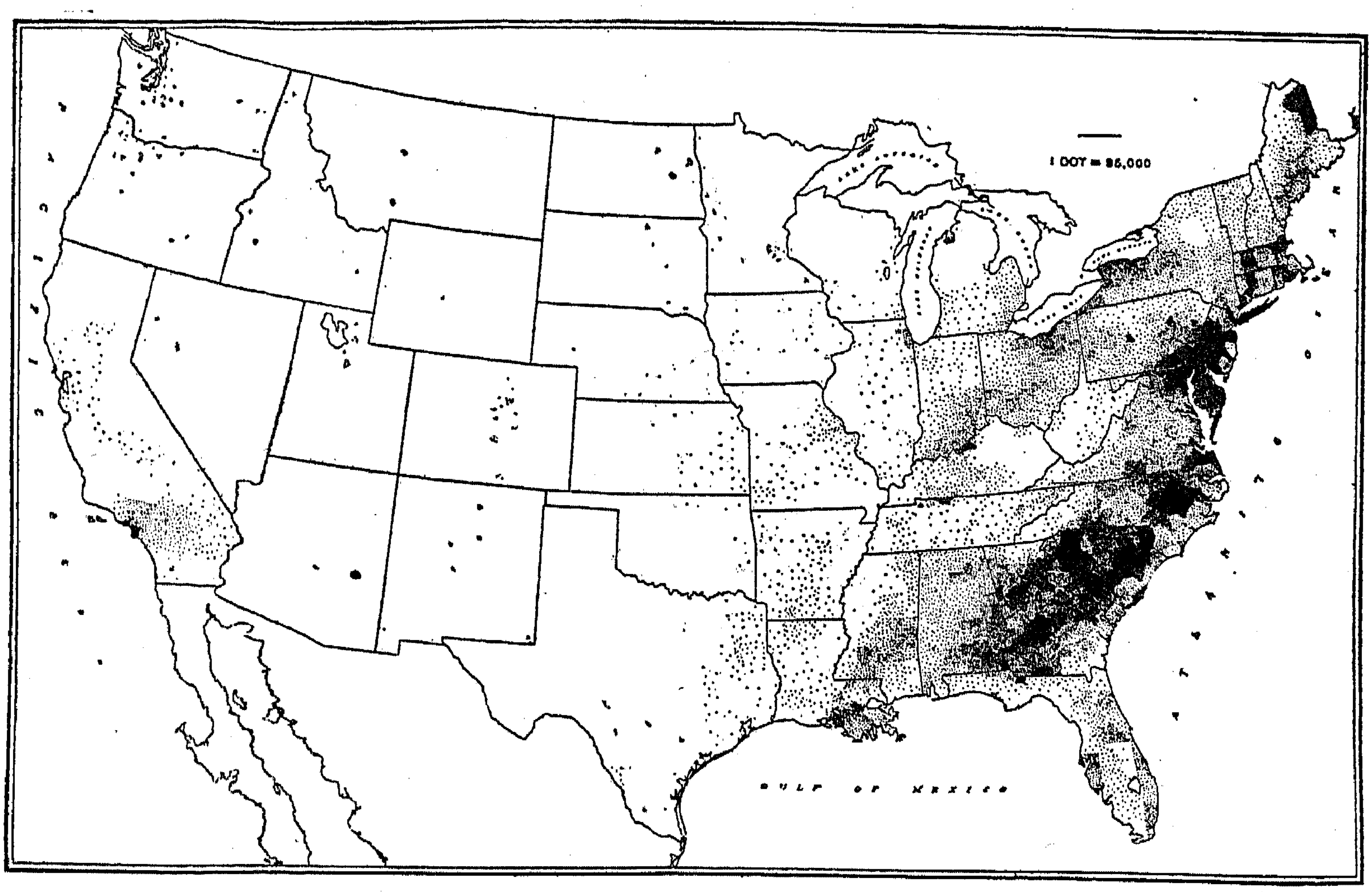
properly spread upon the soil. These high iron, " A " phosphate deposits, as they are called, are awaiting an economical process for their treatment, in order to make them available to agriculture. It is my belief that with cheap electric power, this problem can also be solved from the standpoint of electrochemistry.

I shall now present certain data taken from the thirteenth census of the United States (1910), which, in my opinion, shows the urgent necessity for the ultimate application of developed water powers to the food problem of the future. The total area of cereals harvested in 1909 was about 191,000,000 acres as compared with about 185,000,000 acres in 1899, a gain of about 3.5 per cent. During the same period the production increased only about 73,000,000 bushels or 1.7 per cent. The yield per acre was therefore slightly less in 1909 than in 1899. At the same time the population of the United States proper increased from 76 to 92 millions, or 21 per cent. These figures are significant and authoritative, although it is fair to add that they are affected to some extent by bad weather conditions in the corn belt in 1909. The magnitude of a crop is determined by acreage and yield per acre, but the latter factor is the one which really measures in the long run the efficiency of agricultural operations. The yield per acre is affected by some conditions, such as weather, that are beyond the control of man, but no one can say that by the proper use of fertilizer, other things being equal, the production per acre can not be increased many fold. This is indicated also by the fact that European acres before the war were yielding from two to three times that of our own. Leaving aside the questions of proper tillage, plant breeding, seed selection and other important factors in crop production, as not germane to the present subject, let us inquire what the country was doing in the use of plant foods on our soils.

According to the last census report, the total number of farms that reported expenditures for fertilizers in 1909 was about 1,800,000 or about 29 per cent of all farms. The total amount expended for fertilizer in 1909 was about $115,000,000, and the average amount spent per acre of improved land (based on the acreage of all farms) was 24 cents. This average is made up of variations of from one cent per acre in the West, North Central, and Mountain sections to $1.30 in the New England division and $1.23 in the South Atlantic. It is, of course, true that the differences in the expenditures for fertilizers reflect differences in natural fertility of soils, in character of crops grown, in cus-

tomary methods of agriculture, and in freight rates on commercial fertilizers from mill to market. But nevertheless the value of all crops grown in the United States in 1909 was very nearly five and one-half billion dollars, in the production of which some one hundred and fifteen million dollars-worth of plant food was used, or just a trifle more than two per cent.

I submit that these figures speak for themselves, and that the conditions have not been materially changed in the intervening years between 1909 and 1916. What more strenuous argument is needed for the development of our water powers to the end that they shall be set to work on the production of plant food for



DISTRIBUTION OF FERTILIZERS IN UNITED STATES IN 1909

the coming generations? Is it not indeed a duty that the present generations owe to posterity?

Before concluding, I invite your attention to the most illuminating map taken from the last United States census, which gives the expenditure by farmers and the distribution of fertilizers for 1909. This shows at a glance the truth of much that has been set forth in preceding paragraphs, and it shows much more. This map might be made the basis of a popular travelogue. If we use imagination, we can picture to our minds the strenuous drive of the Aroostook County, Maine, potato industry, the efforts of the truck growers of Massachusetts to feed the teeming millions of their congested cities and manufacturing districts. We pick out the high grade wrapper

tobacco section of Connecticut, whose product is worth dollars per pound and is found worthy of lavish expenditures for fertilizers. We see the effort to supply the New York, Philadelphia and Baltimore markets, and follow the truck gardens down the Jersey coast to the tip of the Eastern Shore of Maryland. Further south we pick up the tobacco belt and the great region where King Cotton reigns supreme, and this King is powerful to exact his annual tribute of plant food. We see the effect of fruit growing in Florida and southern California, these regions which are still too sparsely fertilized. We can see the sugar cane waving in Louisiana, and even trace the national grape juice from the serried grape vines on the southern shore of Lake Erie. We travel on through the great corn belt of Ohio and southern Illinois, until we come to the Mississippi, but here, as far as our subject goes, we stop. The great grain producing states of the Far West are busily engaged in taking money out of the bank, but, as far as plant food is concerned, they are putting little or nothing back. It is probably true that all agricultural districts appearing on this map, which do not show up in black or at least dark gray, are to a greater or less extent proceeding along a similar pathway towards the ultimate destitution of our soils..

The task of attempting to present in a brief paper a discussion of so vast a subject as the influence of water power development on the food problem of the future has not been an easy one, and I am fully conscious of the fact that only a few high points within the range of the subject have been touched. It is possible, however, that there are many people in this country who have never yet realized that the potential energy of a flowing river can be transmuted into food and sustenance, and thus indirectly direct the vital activities of a nation. The scenic grandeur of a great waterfall may be a national asset, but I am one of those who see an even greater grandeur and a more valuable national asset in vast fields of waving grain and contented, well nourished herds, which mean, as they always have and always will mean, a contented, virile and industrious population.

Presented at the 321st Meeting of the American Institute of Electrical Engineers, Washington, D. C., April 26, 1916.

RELATION OF WATER POWER TO TRANSPORTATION

BY LEWIS B. STILLWELL

ABSTRACT OF PAPER

The paper discusses the relative importance of water power in its relation to transportation, as depending upon its cost and the cost of competing steam power.

Proportion which " Cost of Fuel for Locomotives " in the country as a whole, in various sections, and in the case of a number of different railroads, bears to " Total Cost of Operation."

Effect of recent progress in art of producing electric power by steam upon water power values.

Power and transportation development on navigable streams.

Illustrations of the limit of investment in developing a water power, as fixed by cost of competing steam power.

Comparative cost of canals and railroads.

Illustrations of comparative speed and power consumption in railroad and canal operation.

THE RELATION of water power to transportation in the United States is a subject far too broad, and in some of its aspects too complex, for comprehensive and adequate treatment in a twenty-minute paper. Like many other subjects with which engineering science deals, the economic factors which determine that relation in any given case depend so largely upon local conditions as to make useful generalization difficult, if not impossible. The best that I can hope to do in the time allotted for this introduction to your discussion of the subject is to point out some of the conditions which determine the value of water power in relation to transportation at the present time, and to indicate roughly how this value may change with progress of the art of producing power from fuel and with changes that may occur in the interest rates upon capital necessary to development.

The relative importance of water power used as motive power to move traffic, in its relation to transportation, in different parts of the country varies, depending primarily upon the cost of water power and the cost of competing steam power as developed by locomotives or by existing or possible steam power plants. Where water power is produced, or may be produced,

by building dams on navigable streams, the production and possible utilization of power are interrelated with the problem of inland waterway transportation, owing to the fact that the construction of a dam may be made to serve the double purpose of developing the power and creating a stretch of navigable water.

Cost of Fuel for Locomotives

The following interesting statistics giving for the Eastern, Southern and Western Railroad Districts, and for All Roads, the "Miles of line operated," the "Cost of fuel for locomotives," the "Total operating expense," and the "Ratio of fuel cost to total operating expense," are taken from the report of the Interstate Commerce Commission for the year ending June 30, 1914:

FUEL FOR LOCOMOTIVES, AND TOTAL OPERATING EXPENSES, FOR ALL RAILROADS IN UNITED STATES HAVING OPERATING REVENUES GREATER THAN $100,000 IN THE YEAR.

	Eastern district	Southern district	Western district	All railroads
Miles of line operated........	62,780	46,587	136,257	245,624
Cost of fuel for locomotives....	$ 104,461,133	$ 33,052,970	$105,286,696	242,800,799
Total operating expense.......	1,004,620,282	348,295,136	847,397,741	2,200,313,159
Ratio of fuel cost to total operating expense............	10.45%	9.50%	12.40%	11.05%

It will be noted that the "ratio of fuel cost to total operating expense" varies from 9.50 per cent in the Southern District to 12.40 per cent in the Western District, the grand average for all railroads being 11.05 per cent. The total expenditure for fuel for the year is $243,000,000.

Obviously, any substantial reduction in cost of fuel would mean an important saving in total operating expense of our railroads. For example, were it possible, in the case of the average railroad, by using water power to effect an economy equivalent to a reduction of 50 per cent in the fuel bill, a reduction of about 5½ per cent of the total operating expense would result; but unfortunately water power can be substituted for coal or other fuel in the operation of railroads only at the price of an investment in hydroelectric machinery, in transmitting and distributing conductors, and in electric locomotives, so great that a saving of 50 per cent in the fuel bill would constitute in itself

an economy by no means sufficient to offset the increase in interest charges upon the investment necessary for electrification. The bearing which such a possible saving would have upon the question of electrifying what may be termed the "average" railroad is shown by the following figures, which are abstracted from a paper "On the Substitution of the Electric Motor for the Steam Locomotive," presented by the writer and H. St. Clair Putnam at the 214th meeting of this Institute. While these figures were prepared nearly ten years ago, additional operating data of electrified railroads now available are corroborative of their general correctness and they are sufficiently accurate for our present purpose. The figures compared are, first, the average for steam operation during five years, from 1901 to 1905, inclusive, as reported by the Interstate Commerce Commission, and, second, the cost of operation by electricity as estimated in the paper referred to.

	Average five years	Estimated cost of operation by electricity
54, Maintenance of way and structures	21.003	22.354
55, Maintenance of equipment	19.524	12.587
21, Engine and round house men	9.451	4.710
22, Fuel for locomotives	11.292	5.702
23, Water supply for locomotives	0.634	.000
24, Oil, tallow and waste for locomotives	0.381	0.250
27, Train supplies and expenses	1.537	1.000
29, Telegraph expenses	1.780	2.000
35, Loss and damage	1.112	0.750
36, Injuries to persons	1.086	1.000
37, Clearing wrecks	0.246	0.200
	68.046	50.553

(The above items are numbered as in the report of the Interstate Commerce Commission, and only items the amount of which is changed by electrification are included.)

The total estimated saving in cost of operation is approximately 18 per cent of this amount, a saving of one-half in fuel accounts, in round numbers, for approximately one-third of the total saving. Reduction in fuel expense which may be effected by utilizing water power, therefore, under average conditions will affect practically but one-third of the total savings due to electrification upon which the question of substitution of electric power for steam will depend in the case of a railroad which may find itself in position to secure the capital necessary to electrify a part of its system.

The following tabulation from the report of the Interstate Commerce Commission for 1914, shows, as might be expected, that the relation which the cost of fuel bears to total operating expense of different railroads varies between wide limits:

STATISTICS FROM I. C. C. REPORT ON RAILROADS, FOR YEAR ENDING JUNE 30, 1914.

Road	Approx. thousands miles of line operated	Cost of fuel for road locomotives millions	Total oper. exp. millions	Ratio fuel for rd. loco. ÷ total oper. exp.	Average tons freight per train (1910)	Average tons freight per train (1914)
A. T. & S. F.	12.4	5.6	60	9.4	298	357
A. C. L.	6.0	2.6	26	10.0	201	225
B. & O.	8.9	5.6	72	7.8	443	620
C. & N. W.	12.7	6.0	59	10.2	261	348
C. B. & Q.	13.1	5.8	62	9.4	381	479
C. M. & S. P.	14.3	7.75	61	12.7	276	380
D. & H.	1.9	1.9	15	12.7	428	532
D. L. & W.	2.6	2.4	26	9.2	545	652
Erie	4.6	3.2	37	8.7	497	593
Gt. Nor.	10.1	5.3	46.5	11.4	520	663
Ill. Cen.	7.7	3.8	51	7.5	364	417
L. V. R. R.	3.4	3.1	28	11.0	536	588
Mo. Pac.	5.0	2.0	22	9.1	240	329
N. Y. C.	9.4	7.0	86	8.2	413	503
N.Y., N. H. & H.	4.6	4.5	49	9.2	293	304
Nor. & West.	3.8	2.9	30	9.7	635	802
No. Pac.	9.7	5.0	41	12.2	429	567
P. R. R.	10.5	9.3	134	6.9	649	729
Reading	2.8	3.2	32	10.0	477	580
Southern	9.8	3.8	50	7.6	237	275
So. Pac.	9.5	4.9	55	8.9	428	431
U. P.	5.7	3.7	29	12.8	432	431
Wabash	4.2	2.3	24	9.6	353	393
	172.7	101.65	1095.5	Av. =9.3%		
All R. R's. in U. S.	245.6	208.4	2200	Av. =9.5%		

It will be noted from this and from the preceding summarized tabulation that fuel cost in general is high upon railroads operating between the Mississippi River and the Pacific Coast, coal being less generally available at moderate cost in this territory than in other parts of the country. For example, while fuel for road locomotives in the case of the Pennsylvania Railroad represents 6.9 per cent of total operating expense, and in the case of the Illinois Central 7.5 per cent, it amounts to 12.8 per cent in the case of the Union Pacific and 12.7 per cent in the case of the Chicago, Milwaukee & St. Paul. While many factors other

than the cost of fuel per thermal unit affect these percentages, no argument is required to demonstrate that the cost of coal is a very important factor in railroad operation, and that any important reduction in this cost means increased net earnings, decreased cost to shippers, or both.

It is a fortunate fact, which frequently has been pointed out, that in certain very important sections of our country where coal deposits are lacking, water power is abundant, and since the cost of competing steam power primarily determines the relative value of water power, it follows that the water powers on the public domain, in general, have a relatively higher potential value than they otherwise would possess, owing to the fact that they exist in localities where coal or oil, or both, are relatively expensive. Further, it is to be noted that these water powers are naturally found in hilly or mountainous sections through which the operation of railroads implies the handicap of grades, in many instances heavy, and consequently the consumption of power at a relatively high rate per ton-mile. Broadly speaking, therefore, these mountain water powers in sections where no deposits of fuel exist are of especial interest and possible value in relation to transportation.

The question whether it would pay to substitute electricity for steam as motive power on a given road, or a given division thereof, or even on a certain mountain grade, can be answered only by exhaustive and competent consideration of many factors, among which the cost of power, while an important one, is not necessarily controlling. It is impracticable, therefore, to attempt to fix with precision as a general case the limit of allowable investment in water power development within which a saving for electrification would be shown, as compared to operation by steam.

It may be pointed out, further, that where cheap water power is available in connection with transportation in a hilly or mountainous country, the conditions which control the extension of a railroad system are affected by the fact that cheap electric power makes it practicable to adopt grades exceeding the limits which experience has established in steam practise. The resulting possibility of shortening lines and reducing the cost of the permanent way construction may be important in new territory, although it must be noted in this connection, also, that as regards new lines in such territory over which traffic for a time is usually light, the investment in hydroelectric plant and in rail-

way electrification is generally greatly in excess of the cost of locomotives.

No consideration of the problem of electrifying a railroad, or a division, or a mountain grade, is complete which fails to take into account the fact that the cost of competing steam power has been decreased materially in recent years by improvements in the design and efficiency of the steam locomotive, or to recognize the probability that further improvements will result from the continued efforts of the many able men who are devoting their energies to advance in locomotive design, with special reference to fuel economy; nor is any consideration of the relation of water power to the operation of a railroad complete which omits consideration of the great reduction in the cost of electric power produced by steam-driven generators which has been achieved within the last fifteen years by the substitution of the steam turbine for the reciprocating engine and by improvements in boiler construction and practise. For example, a 5000-kw. turbine-driven alternator today, at its point of best efficiency, will produce a kilowatt-hour using 20 per cent less coal than was required fifteen years ago by the 5000-kw. units which the Manhattan Elevated Railway of New York installed at its Seventy-fourth Street power house, these latter being at least equal in efficiency to any engine-driven units installed in this country up to that time. Moreover, this reduction in cost has been characterized not only by a reduction in the amount of fuel required to produce a kilowatt-hour, but also by a relatively still greater reduction in cost of plant, as illustrated by the fact that a 5000-kw. turbine-driven unit today costs about $12.00 per kilowatt, while the cost of the engine-driven units to which I have referred was $35.60 per kilowatt.

Still further, the development of the dynamo in large and still larger units in connection with the evolution of the modern steam turbine makes it practicable today to realize still greater economy both in first cost and in fuel consumption, owing to the fact that we now can avail ourselves of larger units than were formerly on the market. This additional gain is particularly marked as regards fuel economy. It is probably conservative to say that a large plant, *e.g.*, one of 100,000-kw. output, using large steam turbines, in producing electric power to meet average conditions of demand as existing in our large cities, or in railway service, will use not more than two pounds of coal where the best steam practise fifteen years ago would have required three pounds.

As in the case of stationary steam plants, so also in the case of steam locomotives substantial progress in fuel economy has been made in recent years, and still further progress in this direction must be anticipated and taken into consideration in connection with future utilization of water powers aiming, in whole or in part, to supply electric power for railroad operation.

Power and Transportation Development on Navigable Streams

The relation of cheap power and waterways, as simultaneously developed by the construction of dams on so-called "navigable" streams, is a subject so complex that I can glance at it only in certain aspects. By constructing a dam at a suitable location on almost any stream of reasonable magnitude, a certain amount of power will be produced and a stretch of navigable water of more or less length developed. What the commercial value of the power thus produced will be depends primarily upon the cost of competing steam power as it is produced, or might be produced, in the same locality, and upon the demand for power for industrial and other purposes. What the value of the resulting stretch of slack water may be for purposes of navigation will depend upon so many varying conditions that profitable generalization is practically out of the question. Each project of this kind should receive the most careful consideration, not only from the standpoint of technical engineering, but also from a broad economic standpoint. No conclusion which points to the investment of an amount of capital in excess of that which would suffice to produce an equivalent result as regards the production of power, the provision of transport facilities, or both, can be sound. Railway rates being now subject to regulation by the Interstate Commerce Commission, the argument that the construction of a waterway possesses an economic value to the community in its effect upon railway rates, loses whatever force it may have possessed before a proper method of protecting the shipper was available. To expend public or private money in constructing waterways for such a purpose is to waste a part of that very accumulation of capital by the nation upon which further development of our resources in transportation, in power, and consequently in practically every form of industry must depend.

As regards power production, investigation of every project aiming to accomplish the double purpose of producing power

and providing transportation facilities, should have reference primarily to the cost of competing power produced from coal or other fuel. As regards the utility of any navigable inland waterway which may result from the construction of a dam, it should have reference primarily to the cost and relative advantages, not only of existing railroad facilities, but of new railroad facilities which the investment of equivalent capital might provide. The fact that it has been the policy of the Federal Government to appropriate public money, from time to time, for the development of waterways serving communities more or less local, and that it has not been the policy of the Government to use public money for the construction of railroads, need not and should not influence the investigation of such a project from an economic standpoint. All investment of capital, whether by the Government or by individuals, which results in accomplishing at a great expense a purpose which can equally be attained at less expense, is a waste of capital, which inevitably implies a loss to the community.

Looking at the project, first, as a power proposition, let us determine approximately the amount of investment in the proposed hydro-electric development, including the dam, which may be justified with reference to the cost of competing steam power. For illustration, we may assume that the water power which will result in the construction of the dam is capable of producing, through utilization of modern hydroelectric machinery, a continuous power output of 50,000 kw. A steam plant to deliver this output might comprise five 12,500-kw. units—one of these constituting a reserve to insure continuity of service. Detailed estimates of the cost of such a plant total $3,185,000, which is equivalent to $63.70 per kilowatt, exclusive of the reserve unit. This figure will cover a plant designed and constructed for permanency and for low production cost. Assuming that the available market is such that the annual load factor will be 50 per cent the output of the plant, when fully loaded, will be 219,000,000 kilowatt-hours, and its coal consumption—assuming bituminous coal of 14,000 B.t.u. per pound—will approximate 200,000 tons per annum. Allowing 12 per cent to cover interest, amortization and taxes, the total annual cost of operating the plant and the cost per kilowatt-hour will be approximately as shown in the following table, depending upon the price of coal.

Price of coal per ton.........	$1.	$2.	$3.	$4.	$5.
Interest depreciation and taxes at 12 per cent.......	$382,200	382,200	382,200	$382,200	$382,200
Operating labor and material.	175,000	175,000	175,000	175,000	175,000
Annual costs, excluding coal..	$557,200	557,200	557,200	557,200	557,200
200,000 tons coal...........	200,000	400,000	600,000	800,000	1,000,000
Total annual costs..........	$757,200	$957,200	$1,157,200	$1,357,200	$1,557,200
Cost per kw-hr. 50 per cent load factor..............	0.35c.	0.44c.	0.53c.	0.62c.	0.71c.

From the standpoint of power production, we may now determine the approximate limit of investment in the proposed hydroelectric plant, including the dam and its appurtenances. It may be assumed that annual operation and maintenance will be $1.00 per kilowatt. The permissible investment will depend directly upon the percentage assumed for capital charges, including interest, taxes and amortization. If the required capital can be secured from investors who are content to accept 6 per cent, the total capital charges will approximate 9 per cent. If it must be obtained from investors who have other opportunities for investment where they will not only receive interest on their investment but also will have a chance to double their money (and what industrial or commercial enterprise can be financed by private capital which does not offer this apparent opportunity?) we must assume capital charges at 15 per cent.

The first cost per kilowatt of maximum hour output equals $\frac{\text{Cents per kw-hr.} \times 4380 - 100}{\text{Capital charges \% of first cost}}$, and the limit of investment theoretically permissible if capital charges are taken, respectively, at (a) 9 per cent, (b) 12 per cent, (c) 15 per cent, is as follows:

Coal at...............................	$1.	$2.	$3.	$4.	$5.
(a) Cost per kw., 9 per cent cap. charges.........	$157	$201	$245	$289	$333
(b) Cost per kw., 12 per cent cap. charges.......	118	151	184	217	249
(c) Cost per kw., 15 per cent cap. charges.........	94	121	147	173	199

The above table, upon the premises assumed, leads to the conclusion, for example, that in a case where coal costs $3.00 per ton and capital can be secured upon terms which make total capital charges 15 per cent per annum, an investment of $147.00 per kilowatt is justified.

Before accepting this or other conclusions from the table, however, it is highly important that the fundamental assumption upon which these figures rest, namely, that the flow of the stream is such that the assumed amount of power (in this case 50,000 kilowatts) will be surely available at all times throughout each and every year, should be verified. The vital importance of this factor, which not many years ago was too lightly considered by some engineers who made themselves responsible for large investments in this field, is now well understood. The failure to establish with certainty in advance of construction the minimum limit of flow has disappointed many expectations and in numerous instances resulted in very serious financial loss. Where water fails, coal must be used, and, obviously, to insure continuity of service a steam plant must be constructed and at times operated to make good the deficit of hydraulic power, even though this deficit should occur during but one year in twenty or fifty years. This means duplicating investment in power plant, and the real value of the water power must be estimated upon a totally different basis.

As illustrating what happens in such cases, let us suppose that, in case of the possible development which we have been considering, the variation in stream flow is such that in an exceptionally dry year, for a short period—perhaps only a few days—water is so low that practically no electric power can be developed. If this possible contingency must be faced, the steam plant must be constructed if it is proposed to supply a power market requiring continuous service, and the permissible economic limit of investment in the water power development is measured by the capitalized value of the saving which would result from using water power as a substitute for steam power when and to such extent as the water might be available. The investment in the steam plant having been made, the possible saving by substituting the water power when available is practically limited to a saving in coal and labor, but it is obvious that the cost of the steam plant, which we have taken to be about $64.00 per kilowatt, must be deducted from the investment which would be permissible if the water power were absolutely continuous and reliable. It is evident, also, that a further sum, representing the capitalized value of the standby charges of the steam plant and of its operating charges while in use, must be deducted from the estimated permissible investment.

If we except the Niagara and the St. Lawrence, there is perhaps

no river in the United States the potential value of which as a producer of power is not radically affected by an occasional period of very low water. In the great majority of power developments on such streams it will be necessary to provide and utilize steam power as an auxiliary. Conditions under which this necessity has developed in practise, and will continue to develop as new projects are undertaken, are so varied that it is impracticable in a short paper to attempt a comprehensive discussion of the economic limitations of the problem. For our present purpose the foregoing illustrations of the limit of investment theoretically practicable where capital is available, as fixed by cost of competing steam power, and the general effect upon that limit of any reduction in the amount of water power continuously available, are perhaps sufficient.

It is an interesting fact, sometimes overlooked, that the reductions in cost of steam power which in recent years has resulted from decreased cost and increased fuel economy of steam plants, has reduced very considerably the limits of investments in water powers which, theoretically at least, were permissible, say fifteen years ago. Within that period the cost of high-grade steam plants of large size has been reduced about $25.00 per kilowatt. The amount of coal required to produce a kilowatt-hour has been decreased approximately one-third, and the capitalized value of this saving is a further amount which must be deducted from the investment permissible in developing a water power.

As regards the stretch of navigable water immediately above the dam and resulting from its construction, it is obvious that the value of this depends upon its relation to navigable water above it and below. In connection with the construction of the dam, it is usually practicable to build locks of any required size.

It is not necessary to point out to members of this Institute the fact that no conceivable general system of inland water transportation could parallel the railroads of this country and perform equivalent service. Whatever the policy of our railroads may have been in the past in regard to stifling competition by boats operating on inland waterways, the controlling and fundamental reasons for the abandonment of approximately twenty-five hundred miles of canals, constructed during the first half of the last century by states or by corporations, are to be found not in that policy, but in the fact that the invention

and development of the steam locomotive made it possible to build railroads which, constructed at less cost per mile, could operate throughout the year, could transport traffic between two given points in a fraction of the time required by the canal, and at comparatively little expense could provide terminal facilities, practically bringing the railroad to the door of the factory and capable of easy extension to meet the shifting requirements of our growing communities.

Canals vary between such wide limits, as regards width, depth, and topography of the country through which they have been constructed, that averages must be used with caution, but it is interesting to note that, exclusive of the Panama Canal, the aggregate length of canals built by the United States Government up to the present time is something less than 1400 miles, the average cost per mile being approximately $80,000.

We may compare with this figure the average reproduction cost per mile of single-track railroad, as fixed by State commission in Minnesota, Michigan and Wisconsin, in 1907, 1900 and 1903, respectively. The reproduction cost as fixed by the Minnesota commission is $44,888; as fixed by the Michigan commission, $26,138, and as fixed by the Wisconsin commission, $30,910. The highest of these, as will be noted is a little more than half the cost of the average canal (exclusive of the Panama Canal) hitherto constructed by the United States Government, while the average of the three appraisals is about $35,000. On this basis a double track railroad would cost approximately $60,000 per mile.

As regards comparative speed and power consumption in operating by electric power, on the one hand, a canal using 100-ton barges, and, on the other, a railroad, it may be interesting to compare canal operation, using electric power, with results attained on the electrified portion of the New York, New Haven & Hartford Railroad.

The following data are abstracted from a paper by Mr. H. S. Putnam and the writer, presented at the 226th meeting of this Institute, March, 1908, and relate to the canal of The Lehigh Coal & Navigation Company, extending from Coalport to Bristol in the State of Pennsylvania:

Length, L. C. & N. Company's Canal, Coalport to Bristol, 106.2 miles.
Total number of locks: Lehigh Canal, 48; Delaware Canal, 22; Total 70.
Size of Barge used in test: length 87 ft. 6 in.; width 10 ft. 5 in.; draft 5 ft. 2.2 in.

Weight of barge (tons of 2000 lbs.): empty 23.8 tons; load 113.2 tons; total 137 tons.

Watt-hours per total ton-mile, 4-boat tows, about 23 watt-hours.

Watt-hours per freight ton-mile, 4-boat tows, about 33 watt-hours.

Traffic capacity of canal, if all existing locks changed to 4-boat locks: 40 minutes interval between 4-boat tows = 72 boats in 12-hour day, or maximum total tonnage of 72 $\times$ 113.2 = 8150 tons freight in 12 hours.

Maximum speed between locks, 4-boat tows: loaded, 3 mi. per hr.; empty, 4 mi. per hr.

Time for trip of 106 miles, about 85 hours down, loaded = 1.25 mi. per hr. average; about 75 hours back, empty = 1.42 mi. per hr. average.

The watt-hours per ton-mile were determined by test, the company having equipped several miles of its canal with an electric haulage system, with a view to determining the advisability of substituting electric power for mules. It will be noted that the energy required per ton-mile, using four-boat tows,—the average load of the barges being 113.2 tons—was about 23 watt-hours for a maximum speed of three miles per hour between locks and an average speed of 1.25 miles per hour between terminals of the canal.

On the electrified portion of the New York, New Haven & Hartford Railroad, during October and November, 1914, the energy consumption per ton-mile of train weight was 27.3 watt-hours in the case of slow freight, averaging 10.85 miles per hour, and 28.5 watt-hours per ton-mile in the case of fast freight, averaging 18.2 miles per hour.* On this part of the New Haven freight runs are comparatively short and power consumption consequently high, and it is safe to say that in the case of a run of 106 miles, under average conditions of stoppage and interference obtaining on double-track railroads in the United States, power required to maintain an average speed of eighteen miles per hour would not exceed that required in the case of The Lehigh Coal & Navigation Company canal in maintaining an average speed of 1.25 miles per hour.

As regards capacity, it will be noted that, even were the locks of the canal between Coalport and Bristol so reconstructed as to permit operation of four-boat tows, the maximum tonnage in one direction during a twelve-hour period is 8150 tons. In this instance the cost of a double-track railroad would not exceed that of the canal, and it is obvious that its capacity would be greatly in excess of the maximum traffic possible through the

*Article by W. S. Murray in *Railway Age Gazette,* April 30, 1915

canal. For example: a 2500-ton train would carry about 1600 tons of coal, and it would be necessary to pass only five such trains over the road in a given direction during twelve hours to equal the capacity of the canal. On a double-track railroad such trains could be easily operated on thirty minutes headway, which would mean a freight capacity in each direction equal to 4.7 times that of the canal. In the case of the railroad it would be possible, if necessary, to double this capacity by decreasing the headway to fifteen minutes, which, for a speed of eighteen miles an hour, would be entirely practicable.

Without pursuing this subject further, it is evident that, from an economic standpoint, practicable development of our inland waterways is limited to a comparatively small number of rivers, whose channels through a relatively large proportion of their utilizable length are of sufficient depth to permit boats of reasonable draft to navigate them, and which are so located as to permit shipment of heavy tonnage over considerable distances. There are enough of such rivers within the boundaries of the United States to justify the unprejudiced thought of our statesmen and the best efforts of our engineers. The amount of money that will be called for in the development of projects of this kind which are economically sound is so great that every expenditure of public or private capital upon power or transportation enterprises which cannot justify themselves when examined in the cold light of economic science, means delay in the development of other enterprises which would constitute valuable additions to our resources in power, transportation and manufacturing industry.

DISCUSSION ON "ELECTROCHEMICAL INDUSTRIES AND THEIR INTEREST IN THE DEVELOPMENT OF WATER POWERS" (ADDICKS), "WATER POWER DEVELOPMENT AND THE FOOD PROBLEM" (CUSHMAN), "RELATION OF WATER POWER TO TRANSPORTATION" (STILLWELL), WASHINGTON, D. C., APRIL 26, 1916.

David B. Rushmore: As we all know, the world in its advance has been marked by certain definite epochs which have been associated more or less with certain inventions. Unfortunately, not all of these have been recorded in the United States Patent Office, because when man invented power and the use of powder, and the use of fire, the Patent Office was not organized.

It is interesting to see that the civilization which we have in this age is sharply distinguished by certain features, and to my mind the particularly distinguishing feature of this age (which we will say runs back something over one hundred years) is the large use of energy and the great advantage which has followed from its use. Our whole civilization is based on the fact that we consume an amount of energy per individual far in excess of the energy which that individual can evolve.

If we had a complete statement of the facts, we would find that in the last one hundred years there has been an enormous increase in the use of energy per inhabitant. The world, and particularly the United States of America, in the past hundred years has gone through a rapid cycle of activities. Their sequence has been exploration, hunting and fishing, lumbering, mining, agriculture, and finally industry, including manufacturing.

The United States is approaching the industrial age, and that is one of the reasons for some of the economic diseases which we may or may not be able to ward off. The food products are falling off, exports of manufactured products increasing. This indicates a change of flow of commodities.

Now, this being an industrial age, and the age being founded upon the consumption of energy, it is rather interesting to show in brief outline what our principal industries are. At the top stands slaughtering and packing, and it is followed by foundries and machine shops, lumber and timber, iron and steel, flour and grist mills, printing and publishing, cotton goods, men's clothing, boots and shoes, woolen, worsted and felt goods, tobacco, car shops, bread and bakeries, iron and steel blast furnaces, woman's clothing, copper smelting and refining, malt liquors, leather, sugar and molasses, not including beet sugar, butter, cheese and milk, paper and wood pulp, automobiles furniture, petroleum refining, electrical machinery, distilled goods, hosiery and knit goods, and a great many others, in which the value of the annual production is over $100,000,000.

Now, if we withdrew the energy from the world, if we for a moment withdrew the energy from our civilization, we would go down like an infant whose food is withdrawn from it. That

means that our civilization is dependent on energy, and anything which affects the production of energy seriously affects the continuance of our civilization.

Water-power is one of the sources of energy, fixed as regards location and fixed as regards certain attributes and factors which it involves. Energy we must have for our civilization. And what is the attitude, or what is the relation, of the different factors of chemical industries, of food production, of transportation to the source of energy on which they will draw?

First, the problem goes back to the one which we have often considered, that of conservation. The only way to conserve a waterpower is to use it, and the only way to conserve a coal supply is not to use it. A question that is not often raised, but is involved in all of the papers this afternoon, is the great improvement in steam generating apparatus, both as regards the decrease in cost and the increase in efficiency, but we make a great mistake in making use of the cost of coal instead of the value of coal. If the last ton of coal in the world, the final ton, before we go into something else, cost 80 cents, we can all say that its value will be worth more than 80 cents, so that the value of the coal and oil supply which we are not conserving in any way, in fact, we are now wasting it, by allowing such waterpowers to go unused as might be economically developed cannot be determined by the present cost of coal. We are detracting just that much from some future condition of civilization.

Now, if the government, if a combination of individuals, committed some act which robbed our civilization of some of its food supply, or of some other necessity equally great, or even of some of its pleasures, there would be protest. Just that same cause for dissatisfaction exists against ourselves, for we are all involved, not utilizing in the best way we can the sources of energy which are at hand, and whose use would not diminish their worth, and persisting in the use of sources of energy which may ultimately become exhausted. Take into consideration the per capita increase in coal consumption, increase in commodities, increase in industry and transportation, we can see that it cannot go on forever.

The question of waterpower and its relation to these different energies is this—waterpowers are, some of them, susceptible to present economic development. My personal belief is there are many waterpowers in the United States where power can be developed at the power house for much less than steam will ever be capable of being developed, but water power at the power house is different from water power one hundred miles away. Many of our electrochemical industries could be located at the power house in so far as the simple question of power is concerned. Many plants are already so situated, but in the long run the question of the transportation of materials controls.

I do not place the blame for the lack in waterpower development on any one in particular. As I see it, and under the situa-

tion as it has arisen, the people do not understand its value. They sit still, until some one devises and works out some practical way of doing things. When the people are educated, so that they can understand what is going on, then they will take action with regard to the development of such problems.

The railway electrification which has taken place in this country started in the East. The first railway electrification was practically forced by legislation, due to an accident in New York, and that has meant that the railway electrification has been largely based on steam power, on energy derived from coal. There has just begun a larger railway electrification. The transcontinental trunk lines have taken up electrification. The Chicago, Milwaukee & St. Paul is the first one to go into the use of energy derived from waterpowers. They are electrifying 440 miles of their road between Harlowton, Montana, and Avery, Idaho, the first half of this being completed and in successful operation. Some of the results secured are that the cost has been reduced, the weight of the trains increased, and the speed of the trains increased. Prior to the electrification, a considerable proportion, I do not know the exact number, but I think it was not far from 15 per cent, of the locomotives on the railroads were simply hauling fuel for the other locomotives to use. They have been cut out. One of the greatest dangers on the mountain lines is the braking of passenger and freight trains going down hill, and the life of the brake shoe is very short. With electrical motors there is nothing to wear out, not only is the braking done without mechanical friction, but power is brought back in the line.

The very great likelihood is that this road will soon electrify all the way through to the Pacific Coast, and that will force the other railroads to electrification, and force the utilization of these waterpowers, if there is any way of bringing that about. It will require a vast investment, which the railroads have got to provide. If they cannot afford it, they must attract this investment in order to bring about this use of energy. When this waterpower is utilized there will be a saving of other forms of energy to civilization, a saving of coal, which will not have to be burned up until some time later.

The point which we are all looking at is this—the relation of all these factors of waterpower utilization to our modern requirements of consumption. We must bear in mind that once a waterpower is developed into practical operation its supply of energy is continuous and not diminished by time. Some sources of waterpower energy are sometimes inaccessible, sometimes they are expensive to deliver, and sometimes they have a very intermittent stream flow. In certain cases the waterpower can be tied in with another system, a steam station, which, with the waterpower, will develop power for transmission over long distances. In some cases the waterpower plant cannot be physically or economically separated from the steam plant, as a

matter of fact, and the question is always before us how best to bring about the most economic utilization of such water-powers and how best to conserve our fast diminishing coal supply.

F. A. Lidbury: There seems to be no doubt from the papers we have heard this afternoon that whatever other applications for water power may be successfully prosecuted in the future the consumption of water power by the electrochemical industry is one that can certainly, given favorable circumstances, be counted upon to grow very considerably. Mr. Addicks has covered very briefly and very concisely the large number of factors which enter into the employment of water power for electrochemical purposes, and the paper is worthy of study because among those who are not closely familiar with conditions in the electrochemical industry it is common to put the whole of the electrochemical industries in one class as power consumers. They are extremely diverse, their requirements in power are extremely diverse, and the relative importance of the factors of power, labor and other items is also extremely diverse.

We have electrochemical industries which have not succeeded yet in obtaining a footing in the United States because their requirements in power are enormous in extent, and because they require the power at a price at which this country is as yet unable to furnish it, and probably always will be unable to furnish it. We have, on the other hand, industries which you could not drive away from this country no matter what the power conditions were, industries such as that Mr. Addicks is associated with, the refining of copper, in which operation the cost of power is such a minor item that they generate the power by steam.

These two classes of electrochemical power consumers, however, stand outside the limits of that group of electrochemical industries which is chiefly located at Niagara Falls in this country. Mr. Addicks inquired why, in view of the fact that the price at which Niagara Falls power is now sold can not be considered low, and in spite of the fact there is a shortage of power at Niagara Falls, these industries do not go to other places. The answer is—they stay there because they are there. Why are they there? Why did they go there? They went there because at the time when these industries were being developed, at the time of their birth, Niagara Falls offered them the most favorable ground which they could select for their development; it offered them a source of power which then appeared to be reasonably large for their needs, a source of power at a cheap price, and a source of power of an extremely reliable nature. To a great extent it is entirely owing to the fact that at the time these industries came into existence that source of power was there in that form at Niagara Falls that these industries now are at Niagara Falls and not, to a large extent, in Europe.

Mr. Addicks inquired why they do not move from Niagara Falls to other parts of the country, particularly to those regions

where they could obtain power from steam at a cheap price. That brings me to a point which Mr. Addicks might have expressed a little differently. He compares the cost to an electrochemical consumer of water power and steam power, and taking the cost of water power around $20 per horse power per year, which he presumes to be the present Niagara price, compares that with what he conceives steam power can be generated for in large units. In one case he is dealing with a selling price at one's plant including a profit; in the other with an actual cost. The answer to Mr. Addick's question is that these plants have been moving and are moving from the country. Those of you who are familiar with the conditions of the electrochemical industries of Niagara Falls know that when the restriction was put on the power developments at Niagara Falls, in 1906 and 1907, an emigration of electrochemical plants producing materials not for foreign markets but for American markets started and has been continuing ever since. That gives, as far as one can answer the future by surveying the past, the answer to Mr. Addicks' question—Why do the plants stay at Niagara Falls? The answer is they do not, and they will do so, apparently, to a less and less extent. The reason for this is, of course, as everyone knows, that there is at present a power famine at Niagara Falls, particularly on the American side of the border.

The location of such plants at other points in the United States where cheap water power may be available is only possible in the majority of instances where these water powers are most favorably located. I made some calculations a few days ago comparing the cost of water power with the costs of freight on finished electrochemical products. A reasonably cheap freight rate, as you can all appreciate, is vital in the electrochemical industry. It appeared that a thousand mile haul to the center of the area of distribution would be equivalent to a difference in the cost of power, as a rule, of from $10 to $20 per horse power year; in one or two instances much more.

So far as the electrochemical industry is concerned, this question of water power is a vital and pressing subject. Unless the electrochemical industry is able to get the power as it requires it in economically available locations, that industry will relocate, and to a great extent will relocate abroad. By the time you have converted power into electrochemical products, and utilized those electrochemical products, and have figured what it would mean to this country to stop the progress which those electrochemical products have made possible in the fundamental interests of this country, Mr. Rushmore's $100,000,000 a year will look like nothing.

Henry G. Stott: The question that seems to run through all of the three papers might be put in a few words—How can we get power cheaper? Is there any way in which we can develop power cheaper than it is being developed at present, which will admit of the development of the electrochemical processes? If

we go back perhaps we will see why the electrochemical industries today are tending to move away from Niagara Falls.

Fifteen years ago Niagara Falls was unquestionably producing power more cheaply by water than by any other method which could be found in this country. In the meantime the evolution of hydroelectric equipment has gone on quite slowly, as it had a very high initial efficiency. Let us look, on the other hand, at the steam plant. The hydroelectric plant, let us say, has made 10 per cent advance in fifteen years, but in capital cost it has not made any advance at all, if anything the capital cost has gone up, as the cost of labor and material has run up.

Let us look at the steam plant. To begin with, the capital cost of the steam plant in fifteen years has been a little more than cut in two. The next point is that the steam plant is now making power with approximately one-half the coal required fifteen years ago. Those are two enormous points of advantage.

I was very much interested in going over a situation recently which involved tacking on, as it were, a steam plant to a large hydroelectric system. It fell to my work to look into the economics of the situation as well as the engineering possibilities. After going into the situation carefully I came to the conclusion that up to a certain load factor we can today produce power more cheaply, with a lower overall cost, (including fixed charges, and operating cost), by a steam plant than we can by any hydroelectric plant now in existence applied to this particular case.

The overall costs of power were approximately equal at a load factor of 60 per cent. Above that the hydroelectric plant began to show a little better results than the steam plant. Below that point the steam plant was better relatively as the load factor went down.

Now, what we learn from these facts, is simply this—that if we want to produce power at a lower cost than we can do today by hydroelectric plants, we must use some combination of steam and hydroelectric power, the steam plant for the peak loads and the hydroelectric power for that part of the load having load factors of over 60 per cent.

With this combination, as I found in the investigation referred to, the total cost of power, showed a reduction over what could be produced by either steam power or hydroelectric power alone.

There is one feature that Mr. Rushmore touched on, which it seems the whole discussion should go back to, and which we should present to our legislatures and explain the situation as clearly as possible to them; that is, if we can produce steam for the average purposes, for the use of those industries which involves the use of a load factor considerably below 50 per cent, why bother with hydroelectric power at all? There is no use in going into it where the load factor is below 50 per cent. There is hardly a single hydroelectric power left which it will pay to

develop if the load factor is below 50 per cent. The conservation of our limited supply of coal, however, demands that every possible means of reducing the annual consumption of fuels should be enforced for the benefit of posterity.

At the time of the last census there were approximately 1,750,000 kilowatts developed hydroelectrically in this country. I wonder if we realize what that means? That means that approximately 20,000,000 tons of coal per annum are saved to posterity. That, it seems to me, is the real point that we should drive into the minds of our legislators if we can,—we should do everything possible to save our limited supply of fuel.

The improvement in the efficiency of steam plants has been remarkable during the last fifteen years, so much so that, as I said before, the total cost of power has been cut in two. I think there is a possibility of going still further, there is perhaps 10 or 15 per cent left to work on with the present cycle, but the important thing, it seems to me, is to stop the use of coal wherever we can do without it, by developing our hydro power. That would look like a good situation for the government to consider in aiding rather than retarding the development of hydro power.

Gano Dunn: The average load factoı of all the central stations in the country, including water powers, according to some government figures I recently saw which I trust I interpreted correctly, is under 26 per cent, which drives home the importance of Mr. Stott's remarks about the difficulty of a water power competing in the power market with a steam power when water power is only good, or at its best, at high load factors, and cannot hold its own at low load factors with the present efficiency of steam production.

Those interested in the water powers are keenly desirous of finding some way of getting the cost of power down, in a way that might be regarded as intrinsic, as distinguished from the way Mr. Stott referred to and others have referred to of supplementing the water powers with some auxiliary. An intrinsic way would be the development, of processes that could take secondary power, whose costs of interruption under the secondary power plan would not more than offset the gains due to the cheapness of secondary power.

I hope we can get a full discussion from our electrochemical friends in regard to the degree of interruption permissible, and its economic effect in order that we may study to what extent secondary power can be used to absorb the now wasted surplus power of a great many hydroelectric developments. Such absorption would not only give cheap secondary power but would have a reaction reducing the cost of the primary power; in other words, both services would be considerably reduced in cost.

Mr. Stillwell significantly points out the changed equation between steam power and water power in application to the electrification of railways. It is unfortunate that three-quarters of our power consumption is in the east and three-quarters of our

potential water powers are in the west, but if we want to do something about the water power situation, and do it promptly, without going into the realm of doubt, there is a large amount of work cut out by attacking those situations where the water power is actually cheaper than steam power on account of the high cost of fuel, and where the railways would benefit enormously by using such water power as is available. One reason they have not used it in the past has been quarrels among electrical engineers as to which system of equipment was the best. These questions are very rapidly settling themselves. The railroad men, who are conservative, have been deterred from adopting electrical systems, not knowing how soon they might be changed. In introducing electrification upon the railways it has required large amounts of capital, and capital has been difficult to raise in the last decade on account of rate regulations and similar restrictions, as well as on account of the general attitude of the public; and the railways have felt that it would be better to "suffer the ills they have, rather than fly to others they knew not of." It is for us to show that this time has passed, and that the time for the more general electrification of the railways is at hand.

If those interested in water powers, and if those interested in the electrification of railways, especially in the Pacific and mountain states, will devote their energies to bringing the various interests and engineers together, so that there may be mutual understanding, we can at least make a good start by using such water powers as at present can be used to advantage. Once we started, there would be indirect advantages of electrification that will start a general movement and will show that these indirect advantages have, perhaps, been underestimated, and there will then be equipped with water power many railroads which now think they are not quite ready for the equipment.

J. B. Whitehead: It has been emphasized that the cost of electric power from steam plants has been decreasing while that of power from water plants has remained practically stationary. The explanation lies in the general low efficiency of steam plants, offering, therefore, opportunity for improvement and also the lower first cost due to the development of the steam turbine.

The question arises—would it in any way be possible to improve the showing of the hydroelectric plants in the same directions if efforts corresponding to those exerted in the steam problem were also directed to the water plants? While improvements in the efficiency of water power plants, comparable to those possible for the steam plant, may not be looked for, it should be possible, in certain types of plants, to reduce the first cost of the station. Savings should be possible in an aggregation of electrochemical industries and a water plant in which the generating station would operate at moderate voltage and with the elimination of high-tension control and protection. It would also appear not impossible to have the generating station

under these circumstances, practically of an out of door type, with such simplified control as would be necessary, located in one of the industrial plants. While this does not attack the larger cost of the dam and reservoir it seems to offer some opportunity for further reduction of cost of the station.

L. H. Baekeland: The standpoint of the chemist or electrochemist can be summed up in this way—we know how to take care of the chemical side of the proposition, but we are enormously hampered by the lack of cheap power. We hoped that you, electrical engineers, were going to help us in our needs. But when you talk so hesitatingly about the possibility of our water powers being cheapened, and, on the other hand, when we consider that our increasing steam power plants will exhaust so much the sooner our available supply of coal, I must say that I feel somewhat disappointed.

The situation is as follows: In some of our electrochemical industries, we are suffering from lack of abundant power even at high prices, say $20.00 a horse power year. The case has been very well stated by Mr. Lidbury. There are certain electrochemical industries where we can afford to pay relatively well for power, provided we get the power at the right locality, the right point for the market, the right point for freight, the right point for raw materials, and the right point for labor. Niagara Falls is one of those places, but the amount of power produced is all taken up, and further development is prohibited by law. Then there are some industries which could not live in Niagara Falls, even if you could supply them with all the power of Niagara Falls, because the price of power there is too expensive, and I cannot better illustrate this than by taking the example of our contemplated nitric acid supply in relation to the defenses of the country. When it comes to making nitric acid for war purposes, it does not matter how much it costs, because it then can be made regardless of cost. Nowadays the people who are fighting in Europe do not figure how much it costs them; someone else will have to pay for that. For example, phenol which in times of peace is rated expensive at seven cents a pound when it is to be used for peaceful industrial purposes was found cheap enough for the making of explosives in time of war at $1.75. The same thing can be said of nitric acid. The Germans, when they wanted nitric acid, did not discuss the question of the cost of power; they simply erected steam and gas power plants as fast as they could so as to become independent from Chile saltpeter in their nitric acid supply. But there is a more important question in connection with this subject, a subject of far-reaching national importance, and that is the production of cheap nitrogen-fertilizers. I am sorry to have to say that in connection with the production of cheap fertilizers, the problem looks much more difficult, because for this purpose, power should not cost more than five or six dollars per horse power year.

There is one point of view which has not been brought out

here; our more expensive water powers in the United States, as compared to those of other countries, are mainly due to the fact that in this country there are always more contemplated enterprises looking for capital than there is money available. The business enterprises of the country are chronically short of money. They carry on so many enterprises and do this as quickly as possible, and this increases rates of interest; furthermore, our methods of banking are rather wasteful as compared with those of Europe. The result is that when we erect a water power the fixed charges which are incurred are much heavier than what they are in Europe for similar enterprises. Our rates of interest here are very high. In Europe people were glad to invest money at three per cent in various real estate enterprises, and in water power developments. In this country, by the time you float the bonds and give the usual rake-off to promoters, bankers and brokers, and after you consider a lot of side issues that are involved, your water power is already carrying fixed charges of $9 per horse power year, and this charge is fastened on the enterprise before you start to operate. This fact makes an enormous difference when we come to consider the cheapening of water power. Who is going to change this and how is it going to be changed, is a matter on which I cannot advise. Our bankers will have to use less wasteful methods and perhaps the Government may have to do its share by utilizing its excellent credit so as to obtain money at low rates of interest.

J. J. Carty: One of the purposes of this meeting was to call attention to the method of making the work of the bankers less wasteful—if that be a proper term to use—by establishing water powers upon a stable basis where the investor could know where he stood from one year to another. Money can be obtained in this country at low rates of interest or at high rates of interest, depending altogether on the certainty of return and the amount of return.

Owing to the obstructions which have been placed in one way and another about the development of water power, prudent investors and conservative bankers, whether they be located in Europe or in America, have found that only a high rate of interest would attract the people away from more stable investments into the vicissitudes of water power development. If I understand the character of these papers submitted today, and the general situation, the main object is to remove the uncertainties which entangling legislation has cast about the development of these water powers and then the bankers and investors will be in a position to reduce the cost of these hydroelectric powers by furnishing capital at a lowered rate of interest commensurate with the lowered risk, which would certainly ensue the moment that stability enters into the chaotic legislative condition.

L. S. Randolph (by letter): Mr. Stillwell overlooks one or two points in regard to the locomotive situation, which I think should be dwelt upon.

The largest locomotives that we have been able to get only give about 4000 or 5000 h.p. and that seems to be the limit for the present length of locomotive.

Six drivers in series, or coupled by one set of rods have been used but were not found successful, five are being used on some of the Western roads where very heavy grades are concerned, but as a rule four drivers coupled together or the consolidation type, seems to be the limit and in the Mallet many of these are running back to three pairs of drivers coupled together, although the Henderson Mallet on the Erie has four pairs of drivers coupled together, having three sets, making twelve pairs. This seems to be the largest locomotive so far and the problem comes to "what is the limit in length?" as it is practically impossible to increase the cross sectional area of the locomotive, and therefore increase its size in that way. It is as high now as the bridges and tunnels will stand and as wide, and any increase in that direction would mean an entire rebuilding of the permanent way.

So far, the voltages now used permit 9000 h.p. and this has been transmitted by one wire, two wires, of course, would double this, and with higher voltage and smaller amperage still greater h.p. could be transmitted, and with motors under each car, as in the case of street railway cars the limit is almost infinite.

Another point that should be considered in figuring on the economy is that the coal consumption is really a comparatively insignificant item. If one studies the development of the steam locomotive he will find that for years and years, in fact, up to the last five or ten years comparatively little attention was paid to the coal consumption. This was due to the fact that the addition of one or more cars would add to the income of a railroad enormously greater amounts than the cost of the additional coal; so that all the development was towards increasing weight, size, lessen track resistance, etc., so as to get the highest possible hauling capacity for a locomotive. Some five or ten years ago the limit of the size of the locomotive was reached, and therefore the limit of the size of train it pulled. Attempts were made then, not to reduce the coal consumption so much, but to get a larger capacity out of the boiler and a larger h.p. capacity out of the coal consumption. We had from this, the introduction of super-heated steam and feed-water heaters, which were adopted not so much towards the saving of coal as for the increased capacity.

The application of electricity to steam railroads is indicated at the present day wherever the density of traffic makes it impracticable to handle readily the traffic with the steam locomotive, as a case in point, it is stated that on the Elkhorn Electrification of the Norfolk & Western Railroad in West Virginia, four or five electric locomotives handle the work that required seventeen Mallets of the largest type.

Wherever such a state of affairs exists as just mentioned, electrification will give large returns on the investment.

Lawrence Addicks: I think we must all be struck in this discussion with the philosophic tendency which it has taken. It shows that the engineer of today has to be a political economist, a conclusion at which he has been too long in arriving.

As to Mr. Lidbury's discussion I think it is safe to say that power could be sold for $20 a horse power year from a large plant, meaning perhaps a 25,000 or 30,000-kw. plant, but I qualify that to this extent, that we assume the prices for fuel, labor, etc., that prevailed up to a short time ago, and not the high prices that are prevailing temporarily on account of the war situation.

As to what Mr. Stott said about the load factor, of course, a number of us in the electrochemical industry feel that we have a 100 per cent load factor, and the question does not enter there as in public utility work.

As to what Mr. Stillwell said about interruptions of service, my feeling is that it is not practicable to talk about diurnal interruptions, in order to decrease the consumption of power, of three or six hours a day—I do not believe it will work out satisfactorily, except in some possible case such as the carborundum industry, where the whole furnace is torn down after a certain number of hours run. I do think there is a possible solution, which seems a little fantastic. Suppose we took Niagara Falls and put the whole four million horse power in water wheels, and that it was agreed that the plant should be shut down every Sunday morning, for say six hours, so that we could turn the water back into the river. In this way you would satisfy everybody. You would satisfy the power people, because they would get the power which they require. You would satisfy the conservation man, because he would have the scenery, and he could see it once a week. It would satisfy the hotel man, because more people would come up to see the river turned back than came to see it running in full force.

Allerton S. Cushman: Mr. Addicks has referred to his impression that the gentlemen who have discussed these papers have treated them from a philosophical viewpoint. Thathas not been the impression made upon my mind by most of the discussions. It struck me that many of the engineers were principally interested as to whether water power or steam power would be the best paying investment under present load factor conditions. My own mind has been more exercised with the probable future needs and conditions of the country than with dividend prospects under present conditions. If it is true that we are to expect a population of two hundred million people in this country within the next half century or so, it is about time to begin to study the power requirements of the future and to discuss water power development from a somewhat broader viewpoint. For my part, if it requires for the time being a sub-

sidiary steam plant to make a water power plant pay, I would rather have it that way than allow our water to continually run to waste. This may not sound very practical, but surely there is such a thing as building and preparing for the future. Moreover our electrochemical industries need water power, and already in some cases are going abroad to find it. I am at least practical enough to realize that if we are to have cheap water powers we must have cheap money to develop them. The government can borrow money at low rates, or the government could guarantee or endorse water power bonds under properly safe-guarded conditions. I for one can see no harm in such a suggestion, and would advocate such a plan if I had the opportunity. To my mind it is one way of keeping the government out of business, but I confess I would rather have our government develop those water powers that ought to be developed than not have them developed at all. The government might build the dams and lease the power under proper regulation, but this would mean the use of government money, with the usual pork barrel danger. Under a guarantee plan, the government would use nothing but its credit unless some water power failed to earn the interest on its bonds. Why should Norway get cheaper money than we for water power development? Some way out of this situation ought to be found, for many people in this country believe that these things are worth doing and worth doing now.

L. B. Stillwell: The last speaker, Dr. Cushman, made a statement which it seems to me is fairly debatable from an economic standpoint. To my mind the proposition that the government should endorse water power bonds is economically as unsound as—possibly it is worse than—the proposition that the government should build a system of canals to parallel our railway systems. The government never yet has been able, I think, to father industrial enterprises or transportation enterprises with that degree of scientific discrimination which is essential to a right result.

Private capital in this field needs no endorsement by the government. What it wants from the government is security of tenure—definite title or definite lease—so that it can at the start before making its investment estimate all the essential factors which it must know in order to justify investment.

Until we have evolved a very different system of economic administration of government in this country, I should be sorry, indeed, to see the government embark upon a plan of endorsing water power bonds.

I do not know that there have been any points in my paper which have been discussed that I need refer to. Our president has touched with great clearness and with emphasis upon the point made by Dr. Baekeland in regard to the high rate of interest. I believe that the high rate of interest which we have to figure when estimating a water power development would be

materially reduced if we could secure a definite tenure and if we could feel sure that the going concern would not become an object of unjust attack through the power of taxation. It is the fact that these factors are today uncertain which in my experience frightens investors away from water power development.

The one thing that we need to do—we engineers and all of our citizens who understand the economic facts—is to educate the public and to assist our legislators to get the economic facts in proper perspective in order that we may secure legislation that will permit us to go ahead. It is nearly eight years now since the agitation began in regard to western water powers, and it would be hard to name a water power of importance that has been taken up and developed *de novo* during that time. There are a number of cases where plants have been extended, where a growing business and the fact that money was already invested compelled an extension, but the number of new ventures is not great.

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WATER POWER AND DEFENSE

BY W. R. WHITNEY

ABSTRACT OF PAPER

The United States has no adequate domestic source of fixed nitrogen. Nitric acid is an absolute necessity in the manufacture of any form of explosive as well as in the production of dye stuffs. Ammonia or nitrate compounds are in increasing demand as fertilizers. The present dependence upon Chile is a menace in case of war and involves the payment of export duties and profits amounting to nearly $5,000,000 annually in times of peace.

Home production is wholly a question of initiative and proper utilization of water power. Failure to establish the industry in the past has been due to economic conditions, such as the relative proximity of Chile and the impossibility of competing with the cheap water powers of Scandinavia as well as the lack of a near-by agricultural demand. The growing need for fertilizers, the desirability of establishing a dye-stuff industry and especially the feeling of uncertainty in international relations make a reconsideration desirable.

National safety demands the development of a nitrogen fixation industry whether it be self-supporting or not. But, the industry once established, the products would be of the greatest value in times of peace and many other industries would be stimulated thereby. Thorough industrial organization is the best preparedness for either peace or war.

Each of the processes under consideration has advantages. The problem is many-sided and far reaching and hence it is very desirable that the various government departments concerned, those of the Army, Navy, Agriculture, and Interior, with their skilled staffs and expert knowledge, should cooperate in determining the course to be taken. Immediate action is very important, since at least two years will be consumed in getting any process available into operation, after a decision is reached.

VIEWS on the relationship between our water power problems and the problems of national defense are as different as they are numerous. No one is safe in assuming that he has, for long, held the correct view, for the correct view changes rapidly with the conditions, and these changing conditions are not entirely under control. There are a few facts which it may be wise to review because of the changing conditions referred to, and because all of us are interested in national welfare.

A group of these facts which relate to what we call fixed

nitrogen should be foremost in our interest. They may be briefly stated as follows. The United States has thus far practically no natural sources of niter or other form of fixed nitrogen, nor has it developed any sources of the artificial products beyond the recovery of ammonia from gas-liquors and coke ovens.

Niter has always been the *sine qua non* of explosives, and with all the complicated developments which have taken place in the field of explosive manufacture, nothing practical has been produced which does not depend absolutely upon niter.

The old type black gunpowder which contained niter, sulphur and charcoal, used the salt as such. The later smokeless powders made use of the nitric acid produced from niter by means of sulphuric acid. The cellulose, the glycerine, and the toluol in gun cotton, nitroglycerine and trinitrotoluol respectively, are wonderful substitutes for the sulphur and charcoal of the former explosives, but what we may call the pepper in the powder has always been the nitro group from the niter.

This means, to those who are considering the question of preparedness for defense, that our sources of niter need a lot of insurance. It is not at all inconceivable that our present available supply of niter in South America might become closed to us in the event of war.

The problem of a home source of niter is an old one in the United States. The material has long been used by our fertilizer industries. Organizations representing agricultural interests have tried to bring about reduction in cost of fertilizer necessities —phosphate, potash, and nitrate or ammonia. We have plenty of phosphate rock in the United States, so that freight rates will apparently be the determining factor in the extent of use of this fertilizer ingredient. In the case of potash we are in bad shape. We have some unlocked sources, but nothing comparable with the German supply. We must learn how to cheaply separate potash from our feldspars, our seaweeds, or our ocean waters, and there seems little chance that this will be economically done very soon.

But when it comes to nitrate and ammonia, it is distinctly up to us. The cost will depend on the way in which we use our water power. The raw materials come from the air and the water, and ought to be free to us. At present we are subsidizing the Chilean government at the rate of \$2.25 per ton, or nearly one and one-half million dollars a year for export duty, besides paying a profit of five to ten dollars per ton to the producers. This amounts to, say, five million dollars annually.

In addition to our fertilizer interests, the country has become greatly interested in the aniline dye and chemical industry question. No single chemical is so generally important to this industry as nitric acid, and with us it is all obtained from niter. This fact seems to be an additional reason for attempting to round up our local needs for fixed nitrogen, determine the advisable steps to take, and quickly take them.

It is practically true that the aniline dye industry is essential to the manufacture of modern explosives. The identical materials which are developed for dyes, now constitute the basic ingredients of the picric acid, trinitrotoluol, and tetra nitro methyl aniline used in the present war. The coal tar products, the acids and the apparatus are common to both dyes and explosives. For this reason, if we are to be efficient, if we are to have plants capable of producing explosives in large quantities when needed, then those plants must be producing useful chemical and dye products in times of peace.

If it were only necessary to dam the small water courses and pump the air through some sort of simple apparatus, in order to get niter more cheaply, the work would be easy. The question is in reality very complicated. It has never seemed worth while to dam the waterways to make niter in this country. In the first place, our farms, except in certain long-tilled or special localities, have not fallen so low in productivity that it pays the farmers to meet the prevailing costs of artificial fertilizer. This condition is a continually changing one, and it is always changing in the one direction. We shall as surely have to come to the extensive use of artificial fertilizer as have all the older countries. Our western grain and corn states are now producing only about half as much per acre as are the eastern states, and the difference is in fertilization.

Secondly, we have been able thus far to procure Chilean niter for our limited explosive and chemical manufacture, while the processes for obtaining nitrogen compounds from the air have been in a state of flux or development. It was a peaceful world-economy which established the first practically operative and successful nitrate plant in Scandinavia. There such plants are close to the cheapest water powers, remote from all other sources of nitrate, and near the best markets. Norway's water powers differ essentially from our own. Nowhere in the United States, not even at Niagara, are there existing grouped conditions such as could compete successfully for cost of power with Norway.

This is not generally remembered, but to engineers it should be plain. In Norway there was the fortunate combination of exceedingly elevated water level, of quite dependable and high rate of uninterrupted flow, with immediate ocean shipping facilities and a world's hemisphere of well established market close at hand. An expensive dam, or any dam at all was frequently unnecessary. Building sites were probably donated. Fertilizers were most extensively used and most of the world's chemicals and dye stuffs were made in the adjacent countries. Under such conditions there was apparently no reason for our country's doing this work, and that is why it has not been done.

It is the new conditions which make reconsideration worth while. One of these new conditions is our recently acquired feeling of uncertainty as to the permanence of peace. Another is our growing need for fertilizers, and a third, our desire to insure our textile industries by producing our own dyes and chemicals. Probably every human being on the earth today who has reflected at all, has been astounded at changes which a few months have produced in the most civilized countries of the world. It is not surprising that some of us should look about more or less nervously to see if our powder is all right.

Judging by past events, I think we are justified in imagining conditions which might effectively interfere with our continued supply of Chilean niter. Difficulties might arise before the salt is mined, as was the case with potash in Germany before the war. Transportation troubles from interference on the ocean, or trouble in Panama might be effective in shutting off our supplies. Perhaps the danger is slight, but if our importations of niter should cease, then all our efforts at dye stuff manufacture would fail, and all our efforts at national defense, beginning with diplomacy and ending with torpedoes, would be as useless as a poem on Spring. If we cannot shoot a gun, explode a mine or fire a torpedo without nitrate, we ought to be sure of our nitrate before we are forced into war. We need powder before we need soldiers or guns. Evidently this is a matter for mature deliberation on the part of those best fitted to weigh the possibilities.

Our requirements seem to suggest some early and effective type of cooperation between the department of the Interior, the Agricultural Department, the Army and the Navy, which departments are most intimately interested and best equipped to form opinions on the separate parts of this subject.

It is not my intention to consider the different ways of making

nitrates, but a few words will show how rapidly the industry has recently advanced.

Since the experiments of Bradley and Lovejoy at Niagara, the Birkeland-Eyde electrical process has come into extensive commercial use in Norway. The Schonherr process, another arc process, has been developed in Germany, and the Pauling process in Austria. The cyanamid and Haber processes for ammonia combined with some form of the Ostwald process for changing ammonia to nitric acid, have both contributed to Germany's nitrate needs. The cyanamid process, using electrical power for making the calcium carbide, which is later employed for chemically combining the nitrogen of the air, was said in 1914 to be represented by 14 different plants, representing an investment of $30,000,000. Since the beginning of the war, this process has been greatly augmented, apparently beyond any other. At the present time, Germany is probably using artificial nitrates exclusively, and the allies are beginning to employ them to a lesser extent.

It is because no group of our national representatives is likely to know all aspects of the nitrogen fixation problem, that the assistance of different interests and departments seems worth acquiring. It seems certain that our demand for nitrates for use in fertilizers, in heavy chemicals, pharmaceuticals, and dyes in time of peace, together with our possible needs for ammunition in times of war, would justify radical steps which any one of these apparent demands, taken alone, might not warrant. It is also probable that if our peace needs were properly taken care of, our war needs would be assured by the identical plants and processes.

It has been suggested that in an emergency, our electric street car and city lighting plants could quickly be turned into nitrate producers. A suggestion of this sort should be analyzed for our government by those competent to judge of the possibilities, and not be left to analysis by a pitiless fate.

It may be worth while to offer an opinion on a few of the questions naturally asked nowadays by the engineer concerning the possibilities of nitrate production in the United States. In times of peace and with present synthetic processes, commercial success is not possible if the electrical power costs are as high as fifteen dollars per kilowatt-year, and there are no profitable by-products. At about half of this rate one or more of the present processes might possibly compete with the natural ante-bellum

prices. This could not be done by the use of small isolated plants, nor less than full day load of power. In other words, it would not attract those who ordinarily sell electric power.

This is not the nation's question, however. It is more a question of whether, in times of dire necessity, we could at some inconvenience and high cost, effectively produce within a reasonable time our own requirements of niter. Could a part of existing electrical equipment be quickly utilized for this purpose? Under such conditions would a part-day load be permissible? Could coal be used for power? I do not answer as an expert, but I think that we may safely say that it would take us a couple of years to get under way with the manufacture on any appreciable scale after the delays which would certainly be connected with our decision to start, were passed. The cost might not be relatively greater than are the increased costs of many other products during war time. Electrical equipment already installed might in some cases be employed, but in all probability this would be calledupon for other uses withgreater advantage to the country. As most of our industrial plants would have to do what they could best do, it seems probable that entirely new plants for nitrate would be called for. I believe this has been the experience abroad. In any of the synthetic processes, extensive and special types of apparatus are necessary: special transformers, special combustion chambers, large capacity air-liquefiers, etc. In the absence of water power such a plant could operate on steam power, but should be placed as near as possible to a coal supply. The possibility of utilizing waste coal, if there is any such thing nowadays, is worth looking into in connection with this question. It does not seem probable that part-time load is practicable even in war time, for the production of nitrate. By the arc process, something like three kilowatt-years may produce a ton of nitric acid, but when the demand amounts to two or three hundred thousand tons of acid per year under war conditions, and requires in that case the twenty-four-hour continual operation of over half a million kilowatts, the impracticability of getting any appreciable proportion of it from the off-peak power of present plants seems apparent. It is only fair to note that one of the processes is said to produce the acid at nearly a sixth of this consumption of power. But in this case, the operation in conjunction with existing power plants seems still less possible on account of the nature of the process.

Nowadays the essentials of national preparedness seem to

require longer periods for accomplishment than formerly. When it takes years to build a battleship, war is not a brief siege. The art of successful defense has become a slow and subtle one. It starts with the high school and the education of children. It gets its main strength from the masterly control of technical industries. It owes its effectiveness to novelties in ways of killing, and its staying powers to business foresight and discreet banking policies. It has been well said in this connection that "there is one line of action which we ought to begin at once, and that is, we should begin at the bottom and prepare our industries."

It has also been pointed out that, strangely enough, many of the most useful modern chemical requirements of war are also the leading chemical products of the industries of peace. The chemist sees that sulphuric and nitric acids, chlorin, caustic soda, gasoline, benzol, phenol and toluol, perhaps the most industrial of the compounds in peace, are also the most extensively required in modern war. Similarly, the engineer knows that the modern air hardening tool steels, the modern lathes, the newest boring mills which industrial advance has developed, are now the necessities of munition production. So that industrial activity is a healthy type of national preparedness for both peace and defense.

But for national preparedness, our industrial activities should be comprehensive and coöperative. Whole fields of national interests should not be left entirely untouched because some other country is already profiting in them, as in the case of nitrates today. When it comes to national defense, we must ask ourselves what necessary supplies may be cut off by war. It is for this reason that England, Australia, Canada and Japan have already established national research organizations.

Preparing for defense is consistent with keeping at work in a proper way along the lines of peaceful, healthy industry. In this way it bears on the subject of water power. The engineer will always have the feeling that the power of falling water is a continuing loss except when it is doing useful work. This is inseparably connected with his first lessons in mechanics and thermodynamics, and is probably right. If a single manufacturing company owned our farms and waterways, it is probable that for reasons of efficiency it would make all the available falling water do the work needed to maintain the fertility of the soil or produce useful products. This would only be doing in a broader way what the potentates of Egypt and Assyria had to do cen-

turies ago, when their irrigating systems were built. But we live under a representative form of government, where the difficulties and delay of getting constructive activity are what it costs us to be democratic.

At least two great processes for fixation of nitrogen have been offered to our government in the past few weeks. I refer to the arc process of the du Pont Company and the cyanamid process of the Cyanamid Company. These are essentially different. No brief discussion can bring out their relative values to our country. I consider both of them of the greatest importance to us.

The duPont process, yielding nitric acid directly from the air, calls for cheap water power. Used in conjunction with the production of explosives and the manufacture of chemicals and dye stuffs, it would be a great boon to America in times of peace, and invaluable in war time. The enormous facilities of such a company, widely interested in large scale chemical production and with one of the largest experimenting organizations in America, would certainly bring the arc process much nearer to that high condition of efficiency which the theory of the process predicts and which sometime will be realized somewhere—I hope in America. There is every reason to expect that there would result the evolution of as many new and useful products and processes as are being continually produced in Europe. Several hundred thousand kilowatts are now employed by the arc processes abroad.

The cyanamid process also calls for cheap waterpower and in large quantity. This process seems, at the present stage of things, to be of the greatest importance to our fertilizer industry because of its economical production of ammonia, the form of fixed nitrogen commonly used in commercial fertilizers. The manufacture of nitric acid and ammonium nitrate for explosives by this process is apparently easy and would be economical at power costs which we ought easily to reach in this country.

It is stated that there were somewhat over 200,000 h.p used by the cyanamid process abroad in 1914, and in the past eighteen months Germany has invested $100,000,000. in this work.

These are both tested processes, and we are interested in their present, and even more particularly in their future developments. In any undertaking by our government which involves the granting of special water power rights, the people should want foresight coupled with active, constructive work. It seems as though we might fairly expect sometime a change in the public spirit,

which now usually views almost any large manufacturing undertaking with animosity and adverse criticism. Possibly through the study of these immediately pressing problems of explosives, dyes and fertilizers by our most competent and interested government experts, sound business criteria may be established for the nation's benefit.

Personally, I have a fear that we are forever shortsighted. I am afraid of the need for national defense which may come upon us like a thief in the night, from war declared in a day, because I fear that impotency which is spread over a century and never really discovered until too late. The most imperilled country of the present war is learning more about national defense than we are at present, and is not likely to forget the lessons. New industrial processes will continue to be improved by those people who are now actively engaged in them. The more extended become the details, by-products, contingent interests and economies in any such line of industry, the more difficult becomes the start in it by an outsider. It is not out of the question that ten years from now the commercial sources of nitrate will be Germany and Chili. The artificial processes will certainly be improved. The natural source will about as certainly deteriorate. What will we be doing in the meantime? It may be entirely safe to depend indefinitely on Chilean supply, but the question should be decided for our country by those who are responsible and will give it careful consideration.

I believe effective good could be accomplished by quick cooperation between those different government departments where lie the greatest direct interest and knowledge. One of these is the Department of the Interior, under which come the group of experts of the Bureau of Standards and the Bureau of Mines. These certainly possess men interested in industrial chemistry, well equipped, and anxious to serve. The Bureau of Soils of the Department of Agriculture has also a corps of men equally well fitted for this work, and particularly interested to that part of it referring to the fertilizer problems. The Army and Navy Departments, busied with the multitude of normal duties of defense, might still lend a great deal of aid and pressure to this cooperative problem, without having to produce the same kind of chemical and engineering experts found in the other departments. The country ought to be satisfied with the joint conclusions of such representatives of its interests.

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THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT

BY GANO DUNN

ABSTRACT OF PAPER

The endeavor of this paper is to present, from the point of view of the engineer, certain aspects of the attitude of capital towards water powers. Actual and threatened laws, popular prejudices, and some cases of unprofitable developments in the past, have retarded the development of water powers, but there are also physical and natural difficulties which handicap hydroelectric as compared with steam-electric plants, and make it essential that a reasonable profit in promotion be offered, in order to induce investment.

The cost of water power is rising, on account of the increasing cost of labor and materials and increasing taxation, and the efficiency of the utilization of water power has practically reached its maximum. On the other hand, the cost of steam-electric power is falling, in spite of a steady rise in the cost of coal, because continual improvements are being made in the efficiency of conversion of heat energy into mechanical power, and still further progress is to be looked for. To offset the disadvantage of the increasing cost of water power there is the possibility of utilizing large amounts of secondary power from hydroelectric plants for industries and process purposes that do not necessarily require continuous power.

The hydroelectric plant usually requires about three times the capital investment needed for a steam-electric plant of equal capacity, and the activity of capital in a hydroelectric plant is very low, much lower than in a steam station and in almost all other branches of industry.

State regulatory bodies have hampered water powers by not recognizing the distinction between bond interest as a compulsory expense paid as the rent for money loaned, and dividends as an earned reward for the risk of the business and skill in management. Another factor that must be more clearly determined in order that the hampering effect of uncertainty may be removed, is the length of time a permit or franchise may run before recapture clauses can take effect, and the question whether these provisions should not cover the power development in its entirety.

Water power should be developed as a matter of conservation, to save our coal supply that is being so steadily depleted. This purpose cannot be served unless the attitude toward water power development is changed and some of the present restrictive factors ameliorated so that investors in water power bonds will be satisfied with five per cent interest instead of requiring seven per cent because of the risks they incur at present.

ALTHOUGH the development of water powers is almost wholly a matter of civil and mechanical engineering, their interests have been largely in the hands of electrical engineers. Until electrical engineers created the art of transmitting power over long distances the usefulness of water powers was local and the extent of their development did not exceed one million horse power in the United States.

During the past two decades electric transmission has extended the commercial water power radius from a few miles up to say two hundred. As the art of electrical engineering has progressed and water power has consequently been transformed from a local peculiarity or advantage to an almost universal utility, an intensive development has taken place, energizing for useful purposes thousands of miles of transmission highways and almost innumerable distribution networks with power which formerly wasted itself in the erosion of stream beds and the heating of of their contents.

The profession of electrical engineering has been stimulated by the reaction of this development and has in turn come to depend considerably upon it. Electrical engineers regard the welfare of water powers as identified with the welfare of a large part of their own activities.

The relation of the American Institute of Electrical Engineers to the government of the United States in connection with water powers is an enviable one and is highly valued by the Institute's 8000 members.

In 1911 the National Waterways Commission of the 62d Congress invited the American Institute of Electrical Engineers to send representatives to the hearings of the commission in Washington. In response, the governing body of the Institute created a special Committee on the Development of Water Powers, authorizing it to testify before the commission and put its expert knowledge and experience in every way at the commission's service.

The services of this committee, composed of the country's leading technical experts on water power, were appreciated by the commission and led to the extension of other invitations to the American Institute of Electrical Engineers to send similar representatives to congressional and departmental hearings in Washington in connection with water power legislation. Among these invitations was one from the Secretary of the Interior, one from the House Committee on Arid Lands, one from the

Senate Committee on Public Lands, and more recently one from the Portland Conference of Western Governors, and others.

The governing body of the Institute has continued its special committee in consequence of these successive invitations and in view of the apparent appreciation on the part of the government that the services rendered by the American Institute of Electrical Engineers were scientific and professional and not commercial or political, that its committee dealt with fundamental engineering and economic principles of hydroelectric development that were outside the field of controversy, and that the function of the Institute being scientific and professional and not commercial or political, its status was one involving a high degree of disinterestedness in respect to matters on which its technical advice was sought.

The present meeting of the American Institute of Electrical Engineers in Washington is held under the auspices of this committee and is devoted to an engineering and economic discussion of water powers in the hope of turning all the light possible upon the subject.

As indicated by the duties honorably discharged by the Special Committee on the Development of Water Powers, the engineer's function has become considerably broader than one of pure engineering. By a group of promoters seeking capital, the engineer is usually engaged to make preliminary studies and trial designs until he selects the most advantageous site for and determines the most satisfactory miminum cost of a given development. His work, however, does not stop here, for he is called upon next to make studies of the probable market for power and to estimate expected revenue and operating expenses, including taxes and depreciation, and further since the relation of engineering and economics is so intimate, the preparation of the economic prospectus usually falls to his lot.

With such a prospectus the promoters solicit the support of one or more investment bankers, and the name and standing of the engineer is an extremely large factor in establishing the confidence of the bankers and obtaining their recommendation of the securities of the project to their clients. The criticisms and objections which the bankers constantly raise in reply to the proposals of the promoters have to be answered largely by the engineer, who often reforms his designs many times and has to prove exhaustively his estimates of revenue, capacity, operating expenses and other items before the bankers take up the project,

if they do. Generally speaking and especially in recent years not more than one project in a hundred passes muster.

The engineer therefore usually develops a relation to the financing of water powers, which finds him on behalf of his employers knocking at the doors of capital and using all the abilities he can honorably employ to invite for his client's project the confidence and support of the experts of capital, and he thus acquires a knowledge of the conditions required by capital to be met before financing can be accomplished and he is enabled to take a broader view of the water power situation than one that is merely an engineering view.

The other papers presented at this meeting deal with the value of water powers to the electrochemical industries, to the food problem, to increased transportation and to national defense. In this paper I shall endeavor to present very briefly, from the point of view of the engineer as derived from experience, certain aspects of the attitude of capital towards water powers.

It has already been implied that no matter how useful a public service a water power might perform, no matter how great the need of a community for cheap power to invite industrial development, no matter how powerful the river nor high the falls, nor anxious the promoters, a water power plant will not be built unless the investment banker or his equivalent supplies the means.

The investment banker, generally speaking, is not a capitalist, but a captain for the capital of others. They follow his leadership so long as his record warrants it and they gladly accord him a commission in return for sound advice and guidance as to yield and security for the investment of their savings. These others are countless and are in part scattered throughout the earth. The complicated interrelations of capital among the great capital-producing nations are at once intimate and delicate so that capital may truly be likened to an international fluid, quick to flow towards its level of advantage and equally quick to cease flowing when that advantage diminishes. Prior to investment, capital is above the law. It must be consulted and courted or it cannot be won, and it usually requires of a suitor a good previous character. These are facts, no matter what may be our individual theories of government, of economics, or of social relations.

Part of the acknowledged "water power situation" is due to the scarecrow of financial losses which, contrary to

popular information, have been suffered in water power investments. In cases where losses have not been sustained the actual yield as compared to the expected yield has been very generally disappointing. It seems conservative to assert in respect to a majority of water power investments today, that if the holders were not already in they would not go in if they were free to repeat their investment. Investment bankers of a decade or more ago sometimes piloted their clients with honest confidence into water power projects sound in the prospectus, but so disappointing in the light of later reality as to cost them their financial leadership and render their successors increasingly conservative.

There has been a considerable degree of popular prejudice and misapprehension that conceives water powers to be almost illegitimately profitable. It has had a share in making them the prey of local hold-ups for necessary real estate, flowage rights, relocation of railroads, local taxes and damage suits. But the most serious cause of the above kind that is responsible for the "situation" consists of the inhibition imposed unintentionally, or perhaps it would be better to say unwittingly, upon the investment of capital in water power enterprises, by certain laws, administrative regulations and precedents.

These laws have been both actual and threatened, and in many respects a threatened law is worse than an actual one in the check it gives to investment. Among such actual or threatened laws are those which, limiting the tenure of a grantee, provide for recapture without compensation or with only such compensation as would involve serious loss, or for the recapture of only a part of a system at a fair value for that part, but that part so essential that without it the whole system could no longer thrive.

There is a large group of legislative proposals that look upon water powers as a source of taxation or of government profits through the sharing of earnings. They lay a tax upon energy output, gross receipts, installed capacity or first cost of a development, which tax, although appearing small, amounts to a burdensome and deterrent proportion of the net profits after bond interest.

The grantee is required to construct at his own cost extensive locks and navigation works in cases where he might seem in justice rather to deserve a subsidy for his service to navigation through the erection of a dam that increases the navigability of the stream for many miles and assists in the regulation of its floods. These services, it would seem, should at least relieve him of the burden of additional cost for the locks, which is a drag upon his profits.

Among other menaces to the security and yield of water power capital is the reposing in an administrative officer of the government of a discretion which, while presumably it would never be abused, permits the possibility of abuse by some one of a numerous succession of incumbents, and often therefore in effect causes the title to millions of dollars worth of property to rest upon normal individual discretion instead of upon definitely stated laws that permit the whole of a given future to be securely calculated upon. While clothed with great powers, such officers do not have the co-relative power to make agreements or stipulations that may be relied upon as binding the government.

There are also agitated serious objections to the combination of adjacent hydroelectric systems, on the ground that this permits monopoly and may be used to enhance the price of power and light to the consuming public.

With commissions for the regulation of public utility rates in practically all of the states of the Union, the combination of water powers can have no other effect than benefitting the public, for on most fundamental engineering grounds combination either actually reduces operating cost or does the equivalent of it by increasing output for a given capacity. It increases the insurance of continuity of operation and permits reduction of reserve capacity. It reduces the proportion of steam auxiliary power and enables advantage to be taken of excessive rainfall in one area to make up for occasional deficiency in another. The joint cost of distribution lines is diminished, regulation of pressure is improved, and the utilization of powers otherwise too small to be successfully utilized is made possible.

The objection to combination seems to be based upon analogy to combinations in other branches of industry and ignores fundamental engineering principles, especially in the presence of protecting state commissions. Successful opposition to combination could only result in increasing the burdens both of the public and of the developments.

Many others of the actual or threatened provisions are not only deterrents to investment, but are at the expense of the public. In this class fall all forms of taxes on output or development previously referred to. It is sometimes erroneously thought in proposing legislation of this sort that these taxes will be borne by the owners of the enterprises, but they are in fact passed on by them to the ultimate consumers. They are added to operating expenses and rates to the public are increased proportionately. The increased rates check the growth of manufac-

tures and the increase of the use of light and render the community less attractive than other communities where, either through absence of tax or through natural advantages, lower rates obtain. With the increasing use of power in manufactures, the attraction of manufacturers to a locality is vitally affected by the rates for power that can be offered. Federal laws proposed for the taxation of water powers have naturally applied only to water powers under jurisdiction of the federal government. They inequitably leave untaxed and free from such discrimination competing private water powers and water powers under state jurisdiction.

It seems difficult on the part of many to accept the conclusion that by the control of rate commissions water powers are forever prevented from becoming bonanzas to their investors. Other kinds of public utility corporations are seen to be duly regulated, but there lurks a suspicion that water powers may form exceptions. While the consequences of this doubt contribute to a complacent retardation of development, the benefits of water power development to communities of large population do not seem to be adequately appreciated.

In some of the governments of Europe so greatly are the benefits of development esteemed that water powers are encouraged.

In addition to the laws, prejudices and past financial history that have retarded water powers, there are physical and natural difficulties of a very real sort which render a reasonable profit in promotion requisite to induce investment.

Power developed by a hydroelectric system must be based upon the minimum or nearly the minimum flow of the stream, unless great cost for storage is warranted. The dam, however, must be strong enough to withstand the stream in flood, often 50 to 500 times the minimum flow. A water power is liable to suffer not only from lack of water in dry season, but it is often partly drowned out at times of flood when high tail water reduces the hydraulic head. For these and other reasons most water powers require auxiliary steam power for reserve.

A large part of a hydroelectric power development consists of transmission lines exposed to lightning, wind and sleet. A water power, unlike a steam power, cannot be begun in a modest way and allowed to grow as its market gathers. The real estate, dam, rights of way, transmission towers and many other portions of the development must initially be of ultimate capacity and cost, hence during the early years there is usually a period of waiting for the growth of market when expenses

often exceed income and owners must not only go without their profits but must often put up funds to tide the project over.

For taking the construction and operation risks and the risk of delayed development of income, to say nothing of the risks of title, taxes and adverse legislation, it can readily be seen that the profit required to tempt investment into hydroelectric projects must be at least as great, if not greater, than that offered by other utilities or industrials.

So far there have been dealt with only the checks to hydroelectric investment arising from actual or threatened legislation popular prejudice and construction risk, but, especially east of the Mississippi River where three-quarters of the mechanical power in the United States is consumed and where there are still undeveloped large resources of water power, there is an additional check that daily speaks with a louder and louder voice ruling out the water powers—even if financing were obtainable—in favor of steam produced from coal.

Increasingly large numbers of water powers that a few years ago would have been considered worthy of development by conservative financial authorities, assuming all legislative and administrative hindrances removed, are now ranged in the unworthy class because they do not meet the supreme test to which every water power project is put in the engineer's office before it can get even to the preliminary prospectus stage. This test is a comparison of the cost of the power produced by water with its cost produced in the same market by steam if some competitor should build a steam plant there.

The cost of water power in general is rising on account of the increasing cost of labor due to shorter hours in the form of three instead of two shifts and higher wages, the increasing cost of materials, and the generally increasing taxation, employers' liability and similar items of expense that are characteristic of industrial operations in the United States. In spite of all these circumstances and in spite of a steady rise in the cost of coal, the cost of steam power is steadily falling.

At equal cost the scales of the consumer's choice almost invariably turn against a water power and decide in favor of steam power because, among other reasons, it is generated in the market where it is consumed, whereas water power has to be brought from a distance and suffers the risks of a long transmission line. Also steam power is more flexible and is free from the influence of dry seasons or floods. Water power must be considerably the cheaper before it can compete.

The increasing introduction of steam power, devouring our coal fields at a time when millions of horse power of water power are undeveloped, is a crime against the policy of conservation. Each new steam plant is an agency devoted in effect to the perpetual consumption of coal, and coal is a limited commodity. While absolutely essential for smelting and practically essential for the heating of our houses, it is not essential for the production of power.

Steam power is consumed only when it is used; water power whether it is used or not. If the power of a water fall is not brought to the neighboring city to turn its wheels, do its cooking, or light its lights, the power is developed just the same at the falls and expresses itself in grinding the rocks at the bottom and the heating of the agitated water. Postponement of coal consumption would be real conservation. Postponement of water power development is real waste.

If water power, instead of being at a disadvantage compared to steam power, were fully its equal as to cost of power delivered and certainty of operation, it would still be at a serious disadvantage when construction is under consideration for an added reason which aggravates the whole relation of water power to capital. This is the excessive capital required for a water power as compared to that required for a steam power of the same capacity.

A typical modern steam electric station, including real estate and every other item of cost up to the distribution system, can be built for $45 per switchboard horse power of output. A correspondingly typical hydroelectric development of the same capacity, for moderate head, including transmission lines and substation, would cost in the neighborhood of $135 per switchboard horse power of output, which figures are in the ratio of 1 to 3.

Capital for a steam-electric station is relatively easy to raise. The natural hazards are considerably less. The property is concentrated under one roof, instead of being distributed over many miles of country. There are no actual or threatened adverse laws to introduce doubt as to the security of investment. Popular prejudices are more likely to favor rather than to be against the economics of a steam station. Large supplies of coal are seen going into it and the public appreciates these must be paid for. The plant, to the popular eye, seems to be hot and busy and entitled to its rewards. In the case of the water power, for reasons that have been mentioned, capital is more

difficult to raise, and besides being more difficult to raise, three times the amount is required. It is not difficult to see why, at equal cost of power delivered if it is a question of building a steam or a water power, the steam power gets the preference, and when, as is increasingly the case east of the Mississippi, the cost of a horse power-hour developed by steam is so much less than when developed by water, the "water power situation" is removed from the court of discussion before a decision is reached, because of the fatal competition of steam.

It may be asked—will the cost of steam power continue to decline, notwithstanding the continued rise in the cost of coal? There seems every reason to expect that it will, for with the best plants of today, improved as they are, the return from a pound of coal is only 17 per cent of the power it contains. Internal combustion engines operated by liquid fuel have not yet cut much figure as large sources of prime mover power, but they are constantly undergoing improvement. In the generation of steam, where boiler pressures of 150 lb. were used a few years ago 275 lb. is now used, and higher pressures up to 400 lb. are under experiment, together with higher degrees of superheat than the past has thought possible, and it is not too much to expect considerable improvement in steam economies from progress already in sight. There is also much latent possibility in the gas turbine. In view of all this, he would be rash who notwithstanding the steady moderate increase in the cost of coal would predict an increase in the cost of steam power.

While the cost of steam power has fallen and is falling, due largely to an increasing efficiency in the conversion of heat into power, and while this efficiency is still so low as to render further increases not only possible but probable, the efficiency of water powers has practically reached its maximum and further reduction in the cost of water power from improvement in efficiency is barred. Reference will later be made to the only direction in which substantial reduction is possible.

The unfortunate necessity of relatively excessive capital throws difficulties into the path of water power in more ways than one. Not only is excessive capital required before the development can be created, but after it is created there is a handicap in the magnitude of the bond interest constituting the principal element of cost of operation—using this term in its broadest sense. Both by the large investment of capital required and the large return to capital appearing in its cost of operation, water power development is led conspicuously into the realm of the relations of wealth

and capital to industry and the social system, which relations are subjects of keen political and economic controversy. The water power problem, being exceptionally dependent upon capital, is the innocent bystander that suffers from the quarrel between two struggling antagonists, both of whom its development would enormously benefit. A unit analysis of the gross operating expenses—using the term as before, in its broader sense—of the typical steam-electric and hydroelectric system I have referred to may be of interest, and is given below for annual load factors in both cases of 50 per cent and coal at $3.25 per ton, delivered.

Unit Analysis of Gross Operating Expenses in Typical Steam-Electric and Hydro-Electric Station of the Same Capacity, 20,000 H.P., Annual Load Factor 50 Per Cent. and Producing Power at the Same Cost. Coal $3.25 per Ton Delivered. Returns to Capital 7%

	Steam station per cent of total gross operating expenses	Hydroelectric station per cent of total gross operating expenses
Administration	4.0	4.0
Ordinary operating expenses (except coal)	10.6	4.8
Coal	48.9	....
Taxes and Insurance	6.7	2.8
Depreciation	10.8	11.0
Bond Interest	19.0	77.4
Total	100.	100.

As will be seen from the table, bond interest is the largest hydroelectric expense. In the typical case considered it constitutes 77.4 per cent of the total operating expenses. In the steam station it is only 19 per cent.

The largest expense in the steam station is coal, amounting to 49 per cent of the total. This everyone can understand and nobody begrudges; but there is a small body of opinion which considers all interest usury and to this group the fact that over three-fourths of the cost of producing power in a water power plant represents interest is almost equivalent to saying that the cost of water power ought to be reduced by three-quarters. The whole cost for coal in the steam station is only two-thirds of the cost for interest in the water power.

The classification of bond interest in each case under the head of operating expenses is not customary, but is done for the purpose of giving a clear conception of the radical difference between the compulsory items of expense in the two types of stations.

There is a tendency in many quarters to regard bond interest as profits. This is fundamentally erroneous. It is comparable to regarding the rent a grocer pays for his store as profits. His profits do not begin until after the rent is paid under penalty of

eviction, and similarly the profits of a water power do not begin until after the bond interest, which is rent for the borrowed money, has been paid under similar penalty of eviction by the foreclosure of the mortgage. The holders of the bonds have no interest in the profits of the development. Their returns are set by the prevailing rate of interest in the bond market, and not by the prosperity of the enterprise. They get their returns, in theory at least, whether there are profits or not. It is true that bond interest is sometimes in default, but the holders have the right to take possession of the pledged property, foreclosing and recouping themselves out of the proceeds of its sale for both principal and defaulted interest. It is partly by regarding bond interest as profit that the impression that water powers are very profitable has gained acceptance.

It is natural for a spectator surveying a hydroelectric development to gain the impression that the power comes from the water, which, costing nothing, should render the power cheap. It is evident to a spectator that outside of bond interest the operating expenses of a water power are relatively very low, being in our typical case only 22.5 per cent of the total, which includes ample allowance for depreciation, taxes and insurance. But so much of a dam is in hidden foundations and in parts under water and so much of the long transmission line, rights-of-way and power house and substations is out of view to a spectator, that even though he be liberally inclined towards the deserts of capital, he constantly underestimates the amount of capital invested and neglects to include in his conception of the cost of the power, adequate charges for the service of this capital.

Business men know that profits depend not only upon excess of price over cost of product, but on " turn-over— ", which is the ratio of aggregate sales to capital.

If we compare a steam-electric with a hydroelectric power of the same capacity in both of which the selling price of a horse power-hour is the same, we must permit out of this selling price a greater proportion of gross profit in the hydroelectric or we cannot yield the same return to capital, since there is three times the capital to be served. In other words, there is only one-third of the " turn-over ". The activity of capital in a hydroelectric plant is very low, much lower than in a steam station, and much lower than in almost all other branches of industry such as manufacturing.

Certain public service commissions have hampered water powers by not recognizing the distinction between bond interest

as a compulsory expense paid as the rent for money loaned, and dividends as an earned reward for the risk of the business and skill in management. They have in effect ruled that the total return for bond interest and dividends together must be limited to a certain amount—eight per cent in the recent decisions in California. The result of this in attempting to secure new capital at a time when bond interest rates are tending to rise is going to be the same as if a grocer, when his rent is raised because of improvement in the opportunities of the neighborhood, should be ordered to accept smaller profits in order to keep the total of his rent and profits the same as before. If he were free, he would decline to do business under such conditions, and if not free his plight would be a warning to others.

There has been considerable discussion about the length of term for a permit or franchise after which recapture clauses can take effect, and those interested in water power are not agreed seemingly because of difference in approach to the problem rather than difference in conviction as to the effect of certain provisions.

For a simple water power unrelated to others and not expected to grow, a fifty-year term might at first sight seem long enough to remove from influencing the raising of capital, discussions concerning the favorable or unfavorable developments final to the term. Those who are less concerned over final conditions are often, although sometimes unconsciously, relying upon the extreme improbability of the exercise of the right of recapture, with such loss as it might involve.

But ten years of the fifty would often run between the granting of a permit and the time a bond issue was put out and construction commenced, and three years more would often run before operation began, so that the recapture conditions might indeed come within the life of a forty-year bond and have a sentimental, if no other, effect upon its acceptability and price.

But growth is a characteristic of successfully located and successfully managed water powers, and ten years after the completion of construction perhaps the development of a second location further up stream by the same company becomes desirable. While a fifty-year permit for the new development may have no disadvantages, the new bonds of the company must take into view the approaching expiration of the permit on the first development, which now is only 27 years off, and by the time a three-year period of construction of the second development is completed, will be only 24 years off.

We now reach a time when it becomes of the highest importance to know just what the conditions and effect of recapture will be. If we are successfully to solicit capital for our new venture and if we are to continue to be able to invite industries to locate and develop in our territory, building extensive factories and communities in the security of long-term power contracts, the possible recapture of the original development must contemplate taking over not only the dam site, which is all certain proposed laws have included, but the transmission lines, substations, steam auxiliaries and all appurtenances and adjuncts that make the development an operating whole. The existing power contracts and all other contractual obligations of the development should also be part of the obligation of recapture.

In default of this the application for new capital will be unsuccessful, because there will be feared a limitation of opportunity and a disorganization of the management, possible liability for unfulfilled contracts and possible loss from recapture at a depreciated physical, instead of a fair, value.

If recapture is to be on terms involving a known definite loss—in several bills reversion of dam and power house without compensation has been proposed—an appropriate sinking fund must be set up to offset this. Suppose such a sinking fund to be one per cent of the cost of the original development and to be set up thirty years in advance of the expiration of the permit. This 1 per cent expense seems small; but if we consider that the total return on the cash cost is not likely to average over 10 per cent, of which, for purpose of illustration, 7 per cent may be regarded as bond interest and 3 per cent as profits, the 1 per cent sinking fund for the amortization of the loss of recapture would absorb one-third of the profits of those owning the equity in the venture and bearing the risks and earning the rewards of management.

Reference has been made in only a general way to term of permit and conditions of recapture in illustration of the kind of problems these questions throw into the path of promoters and engineers seeking to make water powers attractive to capital.

A number of their chief impediments are removed and water powers take on a new aspect when viewed as a source of secondary power in addition to their primary power. Capital for a given output greatly diminishes, market is rendered more stable, transmission lines are cheapened, since industries that use secondary power can locate near the development, and the cost of such secondary power manifests itself so low as to help to restore the effective competition of water with steam. In many cases secondary water power would be so much cheaper than

steam that impetus would be given to the creation of industries and industrial processes now dormant because the cheapest steam power is too expensive. For process purposes, continuous or primary power is not necessarily required, and advantage can be taken in large numbers of cases of the enormous amounts of water power in excess of minimum flow or of partly equalized flow now wasted in other than the dry seasons. If by wise provision we can nourish our struggling water powers with the increased revenue which, generally speaking and without interfering with primary power, secondary power could yield, the total cost of both services would be so greatly reduced that water powers would again in a large number of cases assume the place they held before steam power became so cheap, and, east of the Mississippi, began to rob them of their birth-right. The water powers would then be able to conserve coal, up-build communities by cheap power, and encourage location in this country of industries that now go elsewhere.

If, in addition, the attitude of the public, and in harmony with it the attitude of the public service commissions and of the government should change toward water powers so as to regard them as friends, capital would again flow liberally and the public, the government, the capitalists, the promoters and the engineers would all be highly benefited and rewarded.

But even independently of the cultivation of secondary power a great deal can be done to develop our water powers as they are, especially west of the Mississippi where three-quarters of the water power resources lie, and where, generally speaking, on account of the high cost of coal, water power is normally cheaper than steam power. While for the time being the Pacific states and some of the mountain states seem to be over-developed in respect to water powers,—lacking market, rather than development—there are numerous specific cases where development is urgently needed but deterred by the considerations that have been mentioned. Power consumption per capita in the United States is increasing so rapidly that unless we wish to shut our eyes to the staggering rate at which we are making inroads upon our exhaustible coal supplies, the development of our water powers is imperative.

The West needs them to get power more cheaply than is afforded by the relatively high-priced coal and oil, and with this cheaper power it can in time work wonders in industrial and agricultural development. The East needs them as a source of power cheaper still than the already cheap steam power and as a substitute for the fuel-produced power that is eating out the vitals of our fuel

resources, which should be conserved for purposes that only fuel can serve.

The "water power situation" is costing the country many millions annually in actual loss and in retardation of industrial development.

It has been shown that reduction in the cost of water power cannot be expected from further inventions or improvements in the art of engineering, but nevertheless the cost of water power is susceptible of considerable reduction from improvements in another direction.

In our typical case 77.4 per cent of the cost of production of a horse power-hour was composed of bond interest. The table was compiled on the assumption that money was worth seven per cent for water power purposes. If its owners could be induced to lend it for five per cent the bond interest would be reduced by 28 per cent and the cost of production of a horse power-hour by 22 per cent—a reduction important enough in many cases to turn the scales against steam power and result in the bringing of a new water power into existence.

Or if the case occured in the West, a 22 per cent reduction in power cost would go a long way towards encouraging the use of power for purposes previously out of its range.

A five per cent bond interest for the typical case is not visionary. Railroads enjoy it and many industrials.

Water powers could enjoy it if there were a change of policy towards them on the part of the public, the commissions and the government that would make investments in them secure, remove all but the property taxes they now bear, eliminate the many extra construction costs, expenses, delays, technicalities and injurious limitations they suffer, and bring them to a position of being, under the fostering care of the government, a boon to the public.

The writer, for one, thinks this change will slowly come. It has already started. Little by little the interests of the parties to the controversies are being discovered to be identical. Little by little publicity and the pure light of intelligence will permit economic laws to have their free play and the "water power situation" will disappear, giving place to a rapid development that will benefit our citizens as consumers, strengthen old and develop new industries and save our coal, putting us in a superior position not only with respect to power but in respect to the influence power is having upon the development of all the resources of the country.

DISCUSSION ON "WATER POWER AND DEFENSE" (WHITNEY), "THE WATER POWER SITUATION, INCLUDING ITS FINANCIAL ASPECT" (DUNN), WASHINGTON, D. C., April 26, 1916.

F. A. Lidbury: I am glad this question has been brought up, because there has been for years a tendency on the part of electrical engineers in connection with their valley load problems to assume that the electrochemical industries can offer an easy solution. The tendency appears in various ways. There is the steam central station man who comes to electrochemical manufacturers and says, "We can offer you lots of power at cheap rates if you will only take it for a few hours of the day." When you find out what he means by cheap rates you get a shock; but putting that aside, and putting aside the fact that few electrochemical processes can operate satisfactorily in an intermittent manner, let us see what he is trying to do. He is trying to relieve his prospective customer of the investment portion of the cost of the steam power. What is forgotten is that he is asking the customer to increase his own investment charges.

Putting all other considerations aside, let us see how that works out. The consensus of opinion as shown by the figures given today is that the cost of steam plants may be taken as something like $60 per kw. capacity. I venture to say—and I have consulted some of my electrochemical friends present who confirm the statement—that there is not an electrochemical plant in the country that does not involve an investment of at least $50 per kw. in plant cost. Many electrochemical plants run to several times that figure, and the average would be much higher, and might be two or three times as high. What the central station man is asking is therefore that his customer should increase his investment charges to an extent usually considerably greater than those of which he is being relieved. Intermittent operation is in some cases not possible, in others at least inconvenient; but the fundamental reason why these industries do not gobble up the off-peak of steam central stations is the one just given.

Then there is the question why electrochemical industries do not flock around those water powers which have valley power or secondary power at—in this case actually—relatively cheap rates. The answer is again that the added investment cost, taken in conjunction with disadvantages of intermittent operation, is such as to more than neutralize the advantage of the lower power rate. Partial time operation of electrochemical plants does not therefore offer much hope as a solution of these problems. I am not saying that there are not times when it can be done, but I am speaking now of normal conditions.

From the electrochemical point of view the figures given in Mr. Dunn's paper would require modification. His comparisons between the cost of power from steam and hydroelectric instal-

lations, on the basis of a 50 per cent load factor, would be very different on the basis of a 100 per cent load factor. It is obvious from a consideration of the figures Mr. Stillwell gave this afternoon that water power costs become relatively more favorable than steam power costs as the load factor increases, and vice versa; and, as Mr. Stott pointed out this afternoon, there is under every set of conditions a point where the two curves cross. The load factor of electrochemical plants usually lies well above that point.

There is one corollary which is not usually drawn as clearly as it should be. Mr. Dunn mentioned some of the favorite legislative prescriptions put into bills in connection with water power. One of the most ridiculous of these, which occurs in almost every bill relating to water power, is a provision that preference in the distribution of such power shall be given to municipal and similar purposes. In other words, you must provide the type of power which is most costly to develop with those particular loads which have the worst load factor. It has been sufficiently pointed out today that for that kind of load, even under the most favorable water power conditions, a steam plant will do the work cheaper and better, and it is about time that we got it out of the heads of legislators that the proper, decent and reasonable thing to do is to tie a water power plant preferably to those loads of the worst possible load factor.

In connection with legislation one or two other points must be considered. There is the question of taxation of water power to which Mr. Dunn referred. It has been clearly pointed out, principally in Dr. Whitney's paper, that for certain electrochemical processes, particularly for the fixation of nitrogen, we have got to have power at much cheaper rates than at present in order to permit their development. Specific taxation of water power is not likely to lead in this direction; it simply makes it more difficult to introduce industries which the country vitally needs.

Next, as regards the provision that water power plants shall revert to the government, say at the end of 50 years. What about the consumptive industries that have sprung up around such water powers? In most cases where artificial restraints are not put upon distribution, these will largely be electrochemical plants. These plants will be useless except in connection with the water power plants, and they will be providing supplies of fundamental importance to the general industries of the country. The investment involved in these electrochemical plants will be at least as great as, probably considerably greater than the investment involved in the water power plant itself. That is a matter which should receive very careful consideration —what is going to happen to these plants, to the investment they represent, and to the industries which have become dependent on their products, if by some carelessly drawn reversion clause they are liable to be thrown on the scrap heap at the end of 50 years?

Most of these points are more or less related to the strictly electrochemical side of the question; but I feel very strongly that either the future of most of the water powers in this country will be bound up with electrochemical industries, or there will be no future at all for them.

Lawrence Addicks: What Mr. Dunn says about seasonal variation puts a little different color on this question of off-peak power. I have been thinking of diurnal variation, and I think Mr. Lidbury was in what he said, as I certainly was in connection with what I said this afternoon. If you put to us the proposition what we shall do in the ten months of the year, our first question is—what do you mean by cheap power? Do you mean $10 per h.p. year or anywhere near that figure?

Gano Dunn: That or better.

Lawrence Addicks: What will we do with large quantities of power at $10 per h.p. per year, ten months a year, and nothing for the rest of the time? That requires a business which could be carried on by using the current for a part of the time, and working up the product in other ways the rest of the time, and in the few minutes I have had to consider the matter, I can not think of any case where it looks inviting. In order to comply with the proposition it means that we must use so much power in the business that the cost of the power is the main thing, and we will do anything to get cheap power and shut down the business for two months in the year, during that time paying fixed expenses and salaries.

One of the industries in which such a proposition might be considered is the nitrogen industry by the arc process, and I think it would be a very interesting thing to consider. We are now trying to get the government to consider this manufacture of nitric acid from the air, and we are talking of subsidizing the industry, and if Mr. Dunn will come forward with a proposition which will yield very cheap power ten months in the year, it would be worth considering. The arc process uses about 25,000 kw. per ton of 100 per cent nitric acid. The aluminum industry is another which might be considered in this connection.

John H. Finney: The answer to Mr. Addick's question in connection with the aluminum business is perhaps best found in the fact that we are building today something over 150,000 h.p. in hydroelectric power for the manufacture of aluminum, to work twenty-four hours a day, and 365 days in a year. I do not believe secondary power, even for ten months, would interest an organization such as ours.

I should like to comment briefly on Mr. Dunn's paper. The electrical engineer is essentially an optimist. That may not be apparent from the papers read today, and from some of the discussions, but if he were not an optimist, I do not think he would be found here today talking water power. If he were not an optimist, he would be, by this time, thoroughly discouraged by the stagnation that has existed for the last eight or ten years in

the water power business. If he were not an optimist he would not still be trying to "unlock" as President Wilson puts it, this great natural resource and this tremendous, though latent, asset towards industrial advancement and preparedness.

The purpose of the meeting of the American Institute of Electrical Engineers and of its Water Power Committee here today was to call attention to a phase of hydroelectric development that seemingly has not had much thought by legislators' and department officials who deal with this question.

We thought it might be helpful to stress the important uses to which water power can be put by the electrochemical and similar industries. Congress has in mind the value of water power measured by its public utility use solely, and the vast majority of the water powers of the United States are not in that class and never will be, in my opinion.

The great bulk of the water power in the United States is only available for what might be termed a semi-public use—a so-called private use, it might be, of the electrochemical industries, the semi-public use of power for pumping water on to arid lands; serving as motive power in the electrification of steam railroads; in making fertilizers, or in making nitrates for explosives. These are not, strictly speaking, public utility uses, but are much broader, much more important, in that the energy creates not incandescent lighting for instance, but the vastly more valuable products embraced in increased transportation, or increased agricultural production or new and cheapened products of the electric furnace or electric bath.

The public utility use of water power is mainly that of using it as a part of the combined water and steam generating system and therefore it might be no particular hardship to the public service company to have a given water power taken away from it at the end of a fifty year period, because they could at that time substitute a steam plant, or perhaps another water power plant if it were in reaching distance of their operations, but the great mass of these chemical operations, this irrigation work, this electrification of steam railways, requires, first, *cheap* power and secondly and just as importantly, it requires *permanent* power. These operations require power in perpetuity, and that is another thing that our Congressional friends do not seem to have in mind, *viz.* the difference between permanent use, and permanent rights. Great works of the expensive and permanent character required for the development of water power cannot be financed with the expectation or suggestion that they must be abandoned at the end of a fifty year period, or that money invested in them is subject to suspicion and to grave risk of confiscation in whole or in part.

Permanent works are built to supply a permanent use which so far as we can now see will always be performed in the same way—whether the original lessee continues to perform it or another lessee or the Government finally performs it, does

not greatly matter, it seems to me, so long as it is proposed to deal fairly and equitably with the original lessee. Cheap water power in the United States is only possible with cheap money to build water power plants—every unnecessary property restriction causes dear money and more costly power, and materially limits the available water power resources of the nation, as has been well pointed out by Mr. Dunn and others.

If the Institute can bring about a better understanding of what these industries mean in their importance to the nation, we have felt that we would be doing ourselves credit as leaders in the electrical arts, and we would be doing the nation a service, by pointing out what we consider fundamental engineering principles and fundamental economic principles, without the recognition of which no permanent water power policy can be written by the Congress that will bring about that wide development so necessary to the industrial growth of the nation.

L. H. Baekeland: Mr. Gano Dunn referred to some statements I made this afternoon on the subject of wasteful banking. I would like to explain what I meant. Before doing so, I want to answer the remark Mr. Finney just made. He asked: "What is the real importance of some of these electrochemical industries? I could take, for instance, the manufacture of nitrogen-fertilizer which requires such very cheap power, and for which the market is almost unlimited if it can be supplied at a sufficiently low cost. In all our discussions we have been rather indefinite as to what we mean by cheap power: For instance, in the city of Yonkers, I am charged 12 cents a kilowatt hour for current. I think that is cheap, because I cannot do any better, and furthermore, the matter of annual expense in this case amounts to little. So I do not mind much the 12 cents a kilowatt hour they are charging me. I am kicking more about the ugly poles with which they are butchering the landscape and defacing my property, and I would gladly pay 15 cents per kilowatt hour and call it cheap if the company did not put its horrible poles in such inappropriate places.

But when we speak of cheap power for fertilizers we mean $4 or $5 per horse power-year, twenty-four hours a day continuous service. Why do we want cheap fertilizers in the United States? I was born in a country where farm labor is unusually inexpensive, and I know, therefore, that there is hardly any comparison possible between cost of farm labor in Flanders and that in the United States. In Flanders, farm labor is mostly a family affair. The peasant, his wife and children work in the fields, and they feel happy in doing so. They receive no wages; they work practically for their board, and even that does not amount to much.

When farmers, at such low rates of labor, find it profitable to utilize cheap nitrogen fertilizers—and after all fertilizer is a labor-saving device—when we see again that in this country, where farm labor is incomparably more expensive, we cannot

afford to use cheap nitrogen fertilizer, because it costs twice as much as in Belgium or Germany, then "there is something rotten in the State of Denmark."

We can produce very cheap nitrogen fertilizer by fixing the nitrogen from the air if we have cheap power. The chemical processes to do this are well known and the sources of cheap power are here too. But for several reasons, by the time we develop the power, it has become too expensive for profitable use with these processes. Some of these reasons have been well put forth by Mr. Gano Dunn, and what I am telling you now is not in opposition to his statements. Right here is where our wasteful banking comes into play.

When twenty-seven years ago, I landed in this country, one of the first things which struck me was that most commodities here are cheap enough at their source of production, but they are tremendously more expensive by the time they reach the consumer. If I were to put it in another way, I would say that one of the curses of this country is the unnecessary multiplication of middlemen, and this situation goes against the grain of engineers or chemists who work for efficiency. Sometimes I think we are a lot of fools when we work and put forth our best skill, our best efforts, striving to increase efficiency in power production or in chemical processes so as to decrease the cost one cent, or a fraction of a cent, or to reduce power consumption a few per cent and then, after we are all through with our improvements, our increased efficiency looks like a mere trifle if we compare it with the big gap of waste which has to be bridged between the producer and the consumer.

Now in regard to water powers: Take, for instance, a suitable water-power site, including real estate and water rights. An engineer comes along and sees the possibilities of the situation for water power development. Almost immediately he is confronted with some real estate speculation in which some men have to get rich. The next step is the advent of the promoter who wants to get rich too, and most of the time very quickly. Then comes the banker and the bond-broker, and then finally the water power enterprise gets to the point where the equipment gets into the hands of a manager, and the power is now available to the consumer, who finally finds that it is too expensive for him to use it, because at each step in its development, the fixed charges have been increasing. That will not do for cheap power. Cheap powers in Norway, or other places abroad, are not burdened by those extraordinary fixed charges which were incurred by having to go through all these middlemen. Whenever one set of financiers or underwriters control the whole enterprise from the inception of the water power to the construction of the chemical works and the delivery of the final manufactured product to the consumer, it stands to reason that the final cost of the water power will be cheaper. In some cases here in the United States, I found that the cost of operating water power

represents only 10 per cent of the fixed charges introduced by banking or financing, so that any important reduction of the cost has to be found more in the financial end than in the engineering or operating part of the proposition.

Now, what would you say, for instance, if you started to manufacture sulphuric acid, and if first of all your plant is located on a piece of leased ground where you are compelled to pay such an exorbitant rent because the people who possess the real estate have to get rich by it, and then when you purchase your raw materials, another set of people have to levy considerable profit on this, while you, as a manufacturer, would have to get your share in the manufacturing operations after being confronted then again with a selling agency which would claim high commissions, until finally the product, after getting through the hands of all those middlemen, comes in the hands of the consumer at a greatly increased cost. The up-to-date sulphuric acid manufacturer, in order to make a success of his enterprise, begins by owning land or real estate, and he secures his raw materials directly, and when it comes to selling, he does not have to go through the additional expense of middlemen. Therefore, he can afford to deliver his sulphuric acid at a minimum cost. Somehow, we have not yet reached that point in the utilization of our water powers. It is true that in some cases, none of the intermediaries get very much separately, but in the end, they all get something, and these expenses are multiplied collectively until they sum up to a considerable increase in the cost of power, and that is the reason why our water powers are generally so much more expensive than they are in some other countries.

The remarks of Mr. Dunn are correct, that our capricious and ill-digested methods of legislation on the subject of water powers have not contributed to make enterprises of the kind more inviting, and this has raised the rates of interest at which money could be borrowed for this class of enterprise.

On the other hand, we are told that in Germany or some other European countries, there is no opposition between private enterprises and the government, such as has existed of late in this country. I should point out that this matter was disposed of by the very fact that in many instances, the German government has run these public service enterprises as a monopoly or has become a partner in them. For instance, there is no struggle between railroad companies in Germany and the German government for the reason that the German government owns and runs the railroads.

A short time ago, in studying the taxation system of Germany, I found that the earnings of the government railroads paid about 40 per cent of the total expenditures of the German government, and the general taxes of the country are reduced by this amount. In other cases of public service enterprises, like mines, etc., the government became an important partner in the enter-

prise, and in this way, succeeded in controlling easily these enterprises from within, instead of trying to curb them by drastic legislation from without.

I do not say that we should copy these methods. I merely want to point out where we are laboring under difficulties which might be removed if some way could be devised by which the government could enter into efficient cooperation with these enterprises. Some of the privately owned public enterprises in this country, I am sorry to say, have not always been carried out in the interest of the stockholders who had invested their money in these properties, and this too is a very important reason why capital has become shy and wants increased interest rates so as to make up for any contingencies of failure aside from fear of disturbing legislation. This undoubtedly has raised the fixed interest charges for any similar enterprises which might have to be launched.

In England, canals which once were privately owned, were subsequently bought up by railroads and they proceeded to take great care that the canals could not be used in competition with the privately owned railroad enterprises. In this country, we have become so "socialistic" as to have canals which belong to the state. I understand that in Germany, all the canals are owned by the government, and I know that they are kept in the most splendid condition of efficiency and the government can afford to maintain and improve them even if such action is in direct competition to the operation of its own railroads.

In general, there is a great difference in efficiency in any country when enterprises or the details of government are run by engineers and experts instead of by politicians.

Mr. Gano Dunn, a year ago, in this city of Washington, advanced the idea that an engineer should never mix in matters of government administration. I told him at that time, that I disagreed with him. Then after his interesting paper today, I disagree still more, because he has proved by his own example the versatility of our engineers.

We are encountering quite some difficulty in the problems of government of this nation. But we should not be too impatient. These matters are straightening themselves steadily—only a pessimist can deny this. We are confronted in this country with entirely new problems which have to be treated in new ways. These problems are considerably complicated by the immense and rapid growth of our Republic. The fact is that this country, as it grows larger and larger cannot keep on being run in the easy-going ways of a mining camp. We have come to a point where we have to change our methods, and in this we have to do some experimenting, just as we are doing in our chemical industries. If it were not for direct experimenting, our chemical industries could never have made progress. We are very lucky if, only once in awhile, some of those experiments are successful, and we do not count so much the ones which have been unsuc-

cessful as long as we make headway. These problems cannot be solved by a general formula, inflexible and everlasting. Furthermore, whenever we discuss these problems, we are apt to be carried away by one single point of view or another and on this account, we frequently exaggerate one single feature by looking at it from one standpoint. This is the mistake of most of our politicians. When we talk about these matters, let us discuss them like engineers. Let us use quantitative argumentation and let us impress those of our friends in Congress or the Senate who are really willing to learn that we, at least, can look at the situation with a due sense of proportion by using quantitative arguments and not be overawed by merely qualitative considerations.

C. G. Atwater: The point I want to discuss is contained in the first sentence of the summary in Mr. Whitney's paper, namely, that the United States has no adequate source of fixed nitrogen. I think that point is open to some question. Further along the paper makes an exception of the gas and coke industry.

I presume that Mr. Whitney in writing the paper did not consider the dimensions of these industries nor the present conditions that prevail in them. As a matter of fact, so far from there being no source of fixed nitrogen, there is being produced every year in this country from the carbonization of coal to make coke about 750,000 tons of sulphate of ammonia, or equivalent to that. That figures up pretty nearly to our whole consumption of fixed nitrogen. It is not all being recovered, but it is a source known to be open for the recovery of that amount. There is at present being recovered of that amount about 220,000 tons of sulphate of ammonia per year.

That is a very fair proportion, but it is being largely increased. The development of the coking industry that has come with the present abnormal conditions, though largely from the natural growth of the iron and steel business, has brought about very nearly the doubling of that industry, potentially, within the last few months; that is to say, contracts have been let for some 2600 coking ovens which will produce about 150,000 tons of sulphate of ammonia per year.

Now, as you will see, that is very far from the country being in a position of having no adequate source of fixed nitrogen.

I do not wish to make these suggestions from the point of view of checking or discouraging water power development, but when you come to figure these things out and deal with our friends the bankers and others, these points will have to be considered.

There is a tremendous increase under way in the by-product coke ovens, as I have said, and it will amount to more than I have stated, because I have only referred to ovens actually under contract. There are 2000 or 3000 more under consideration. The business of recovering the by-products wasted in

coal is being rapidly developed to somewhere near the position which it should occupy. That is also being applied to the recovery of nitric acid. It will be possible to convert ammonia from coke ovens into nitric acid. There is no question also that the development of the coke ovens will contribute toluol and other substances essential in time of war.

Calvert Townley: I had an opportunity some fifteen months ago of visiting the nitrate pampas of Chile and of inspecting the methods used for getting out this valuable product. It may interest you if I say, that I was impressed with the possibility of very greatly cheapening that product to the ultimate consumer.

We must remember that for a long term of years the Chilean nitrates practically had a monopoly, that is to say, the output of Chilean nitrates so largely exceeded that of any other similar products that the competition of such products was unimportant. The nitrate earth of Chile was very rich and to work it was very profitable, no matter how inefficient might be the methods of extracting the nitrate, consequently the processes were crude in many respects, and the operators did not seek for the economomies which might have been practised if the pressure of competition had been severe. I am not a chemist but it was apparent even to me, as it would have been to any engineer, that there were possibilities of material improvement in the economy of the production of nitrate.

When I was there, owing to the European war the industry was prostrate. Only about 30 per cent of the plants in the country were in operation, and these were running on part time only. Some 30,000 laborers had been thrown out of employment, and I never saw a more discouraged and disheartened set of men than the operating officials who had to do with this industry. They did not know what was going to happen next. One thing which had happened was that they were studying to improve processes for the extraction of nitrate, and it is usually a safe prediction that when a body of men who have been interested in an industry for a long time have sufficient incentive to make improvements they will make them provided there is any considerable margin to work on.

Before the war the Chilean government received some 60 per cent of its annual revenues from export duty on this nitrate which amounted, in round figures, to about $11 a ton. It is an arbitrary duty which of course can be changed, and because the industry was then almost prostrate the question of modifying this duty was being discussed. If artificial processes for getting fixed nitrogen should be established on a scale large enough to jeopardize the Chilean industry it is only a fair prediction that the Chilean government will reduce its export duty.

There is still a third direction from which a reduction in the cost of nitrate may come. The cost of transportation—bringing

the Chilean nitrates from the pampas where are the mines and reduction mills to the American market, has been abnormally high. None of the reasons for this fact are fundamental; they are all more or less the result of monopoly or of limited facilities and the cost is consequently subject to future reduction should the transportation agencies be improved or competition become severe.

The very live possibility that our country may become involved in war and the pressing need of providing for such a contingency should not blind us to the fact that we have lived many years at peace with the world and are likely to so continue —therefore no plan for producing nitrogen will be economically sound which is not commercially practicable under peace conditions. While the quantity of nitrate in Chile has been seriously depleted it is still sufficient to supply the world for years to come and its early exhaustion can therefore by no means be counted upon. This means that any cost for power which we may now estimate to be low enough to permit the artificial fixation of nitrogen in competition with the natural salts, may have to be radically revised downward later on. That furnishes another reason why we must make every possible effort to cut down our power costs. On the other hand, of course all of the processes for the fixation of nitrogen as now known are relatively new and susceptible of much improvement. I understand that not more than 15 or 20 per cent of the electrical energy required by the arc process is actually used in the fixation of nitrogen. Perhaps some of my chemical friends will correct me if I am wrong.

L. H. Baekeland: It is 2.5 per cent.

Calvert Townley: Well, it is worse than I thought it was. That being the case, is it not fair to assume that with the brilliant minds which are at work on this problem a great improvement is likely to result? May we not hope that the processes will be so improved that the industry can prosper with very much greater power costs? A process with an efficiency of 2.5 per cent which could live and pay $7.50 per h.p. per year could presumably do quite as well with a $22.50 h.p. if the efficiency could be raised to 7.5 per cent. One way to have the processes improved is to get people into the business. We all know that there is no teacher like experience, that necessity is the mother of invention, and that if we can get not one, but a dozen, or fifteen, or twenty, or even a hundred corporations interested and competing with the hope of ultimate profit, such competition will bring out the best efforts of the brightest minds. The result will be that in this industry, as it has been in every other industry with which electricity has been connected, the efficiency will rise and costs will go down, making it possible to use power at a cost which now is entirely out of the question.

Those are to my mind important reasons why we should set ourselves earnestly to the task of getting this industry on a basis where it can go ahead.

One thing very clearly shown in Mr. Dunn's paper, is how large a part the cost of capital plays in a hydroelectric enterprise. No engineer could fulfill his obligation to his client without considering the question of the security of any investment. Technical matters can occupy but an insignificant and minor position if there is a risk that the entire sum put into an enterprise, or any part of it, may be forfeited.

Capital conveys to many minds quite an erroneous notion. We are apt to think of it as something entirely separate and apart from ourselves. We think of a banker as a man who himself puts his own money into enterprises. Now that assumption is fundamentally wrong. Investors are not the bankers, they are the men in this room. They are all of us, and our friends. To be sure we do not individually build water or steam power plants for the very obvious reason that such enterprises require large sums of money and there must be some one who will undertake to find out whether or not an enterprise is right and sound and then get the necessary funds together for the undertaking. That is just what the banker does. He is a sort of Captain of Money. He scrutinizes an enterprise and agrees to or refuses to back it, not because he himself likes it, or because he does not like it but because he knows the sort of investments which his clients, you and I and our friends, are likely to put money into.

Some one said something here this afternoon rather critically about the lack of patriotism in capital. Now, capital is a commodity just like grain, or cattle or clothing. It can be obtained for a price and it goes where it can find the best market. Not one of us would stand silent, accused of lack of patriotism, but who is there here who would put his own savings into an unprofitable or an unsafe enterprise to help develop water powers in the west when he might invest it profitably somewhere else? To rail at the man with money because he will not let us have it at a lower rate than he can get elsewhere is just as unreasonable as to demand that our grocer sell us eggs at 30 cents per dozen when he can get 40 cents from every one else in the neighborhood.

As Mr. Dunn remarked, capital is an international fluid. It flows into channels of least resistance. The price of capital is affected by the same laws of supply and demand that govern the prices of every other commodity. If it is higher in this country than in some other country for any individual class of enterprises it is because that class of enterprises lacks some feature of fundamental value. In Mr. Dunn's comparison of the operating costs of typical steam and water plants the capital rental for steam is 19 per cent as against 77.4 per cent for water. If by creating public confidence in the stability of investment and otherwise making these projects financially attractive the rate could be reduced say from 7 per cent to 5 per cent the annual cost of a steam unit of power would come down 5.4 per cent and that of the water unit 22 per cent.

One thing capital looks for is earning capacity, and another thing is stability. Nearly all enterprises can get capital at some price because there is an abundance of it; but when any project lacks certainty of ample earning power on the one hand or stability on the other, that fact will be reflected at once in the price of capital which will demand a higher return.

One thing America can do to reduce the rent of the capital which water powers need, is to remove all the unnecessary handicaps with which it is now loaded One of these is the lack of stability. Warned by the losses suffered in the past by many water power investors, cautious people now hesitate to incur similar risks; consequently, the source of capital supply is restricted to that extent and a higher rental prevails. If we can eliminate this disability capital rental will fall and the development of the water powers throughout the entire length and breadth of the land will be stimulated.

One speaker referred to the lower price of money abroad He mentioned the paternalism of Germany in handling their railroads and other enterprises, and by inference at least drew a comparison unfavorable to American bankers and their supposed unreasonable demands. As far as my information goes there is no more ruthless financier than this same German banker. He is certainly no more keen to lend his money to an unprofitable enterprise, or at a lower rate of interest, on account of patriotism, than the American or English or any other banker. During my tour in South America, I learned about some methods of the German bankers doing business in those countries. I found that they exacted rates of interest which even the most rapacious American banker would not think of asking at home. They did it for just one reason, local conditions justified the rate and they charged the market price for their money. They could get it and they are going to continue to get it. You can rest assured that when a foreign banker lends his money to hydroelectric enterprises in his country at lower rates of interest than the American banker does in the United States, it is because the foreign investment is more secure, because experience shows that the foreign government is going to protect that investment and the risk of loss is correspondingly reduced.

This afternoon Mr. Stott spoke about the low cost of power from steam and the increasing severity of the cost competition with which water powers had to contend. The more I study water powers the greater respect I have for steam and if water power is to prevail at all, we must do our utmost to bring its cost down to the lowest possible limit. If steam can get down lower, steam will be used and water power will not be developed. But every time the cost of water power comes down a little bit its use is broadened and a certain number of water powers which otherwise could not be commercially developed are worthy of consideration.

That is the task to which I think we should address ourselves.

The erroneous and misleading impression that has so long prevailed in the minds of many people throughout the land who have not studied the problem carefully and which has been reflected in the views of our Congressmen, that water powers are very cheap and enormously profitable, is being gradually dissipated and the facts are becoming known. Congress needs only to learn the facts to act upon them in an effective and patriotic way with the same singleness of purpose with which we would apply ourselves to an enterprise for a client. But the feeling that water power development is abnormally profitable to the promoter is deep rooted and of long standing. It still prevails in many quarters. Some Congressmen believe that the interests of the public are in some way different from or antagonistic to those of the investor and that it is their duty to safeguard the people's cause by driving a bargain, so to speak, with capital and by trying to see how little they can do to induce investors to put their money into hydroelectric enterprises. It would be unfortunate if the government which is seeking to have its resources developed by private enterprise without contributing its credit or assuming any risks whatever should adopt a policy which will just not accomplish the desired result by reason of over zeal in attempting to drive a bargain with the investor who is in no way whatever obligated to supply funds for such enterprises.

George R. Smith: Since going to Congress I have given this subject consideration from the view point of the public as well as the investor. I take it, from what I have heard tonight, we do not all look at it from the view point of the capitalist, the man who invests his money. Now, I agree with you that there should be certainty of tenure, and there should be certainty of a reasonable return on the investment. I would say, in view of what little I have done in the way of helping along legislation that if the members of this Institute are ashamed of the sort of legislation which is before Congress for its consideration, as is indicated by statements made, that they have another guess coming, that there is nothing quite so bad as some of the remarks would indicate.

Ever since the veto of the James River Bill we have been trying to get legislation through Congress that would protect the public and at the same time protect the investor, and up to the present time we are just as far away from that as we were when we started. I think that the Shields Bill is no better, possibly no worse than previous bills that have been introduced on the subject.

I want to leave this thought with you. Mr. Dunn put his finger on the sore spot when he said that public utilities could be regulated by commissions,—but he failed to say what kind of commissions. Mr. Hugh L. Cooper appeared a little over a year ago before a committee of the House of Representatives, having under consideration the Adamson Water Power Bill,

which is similar to the Shields Bill and stated that he was afraid of state legislators and state legislatures because he had seen so many awful things committed by them but had absolute confidence in members of Congress and, therefore, was in favor of Congress enacting a law that would authorize the Secretary of War to regulate the price and service of hydroelectric energy.

A few weeks ago in an article in the *Outlook*, when the Shields Bill was under consideration in the Senate, Mr. Cooper said that public utility commissions created by state legislatures will afford all the protection that is necessary for the public and favored state regulation of hydroelectric companies. I wish Mr. Cooper could understand when he appears before Congress at a time when we are seriously considering a piece of legislation which is so necessary as a thoroughgoing water power bill and makes a statement along one line and then in a short time afterwards makes a statement in the press diametrically opposed to the one he made before Congress, that he cannot be expected to be taken seriously. We understand that Mr. Cooper has shifted his position, but we are not quite so clear as to his motive.

There is a great deal of suspicion abroad concerning the motives of representatives of capital who are advocating water power legislation; some of it is unfounded and some of it has a good foundation, a very good foundation. Now, going back to the matter that I wish to call your attention to, I will say that you have got to permit hydroelectric plants to combine in order to operate them economically. Every man who knows anything about the subject at all, knows that that is one of the fundamental principles of economy in dealing with hydroelectric plants. In some cases a number of these plants have combined, a very considerable number, and the moment plants located in different states are combined, state utility commissions cannot regulate them because the current becomes interstate.

In Minnesota we are about to receive power from Wisconsin where there is a large power plant supplying power to various projects. At the present time, Minneapolis, gets its current from Taylor Falls on the state boundary line between Minnesota and Wisconsin. How can a Minnesota Commission regulate current generated in Wisconsin and brought into our state? How can it tell what is a fair rate under that situation? How can it inspect the books of a plant located in Wisconsin, which sells power to the Consumers' Power Company located in Minnesota? The Minnesota Commission has jurisdiction as to how much the Consumers' Power Company, which is nothing more or less than a distributing company, pays for its current but it has no way of determining whether the price paid by the Consumer's Power Company to the Wisconsin company is a fair and reasonable charge, and, therefore, is unable to determine what would be a fair and just rate to patrons of the Consumers' Power Company.

Nothing short of a Federal Commission authorized to work in

conjunction with state commissions will meet the situation which I have called attention to. Besides, under a Federal Commission, the work now being done by the Secretary of War, the Secretary of Interior and the Secretary of Agriculture, could be brought under a single head thus effecting a great saving to the government and assuring efficient regulation which would rebound to the benefit of the investor and the consumer.

The moment that the promoters, the investers, the engineers and the associations that are giving their time to this subject come to Congress with a fair proposition, fair to the public and fair to the investor, Congress will join hands with them in working out an efficient law. Congress is looking for light, it is looking for information. Members of Congress are also anxious to know why they are persecuted for daring to offer any objection to impending legislation that is offered by what is known as the water power monopoly.

Why, we know and you know better than I do, that the water power interests of this country are controlled by a very few men, the whole policy is dictated by a very few men. Mr. J. P. Morgan of New York City is one of the leadin gfactors, and the General Electric Companies is the great big institution, with its subsidiaries, that controls the situation. I do not object to the monopoly because the development of hydroelectric power economically is a natural monopoly. The thing I object to is the refusal on the part of those owning the monopoly to admit that there is a monopoly and I object to their attempt to deceive the public as to the existence of such a monopoly, in order to defeat legislation having for its purpose the control and regulation of such a monopoly.

Mr. Cooper says in his article in *The Outlook*, that it is not a monopoly—he laughs at the idea, he scoffs at it— and yet we know it is a monopoly. Why do the water power interests try to deceive the public? What can be their purpose? Under such a condition of affairs is it surprising that members of Congress as well as the public, look with suspicion upon any suggestion coming from owners of this monopoly. But as long as the water power interest suppress the facts concerning the monopolistic tendencies of hydroelectric development, Congress of the United States cannot be blamed for its refusal to be rushed off its feet in the consideration of water power legislation.

D. B. Rushmore: I need not say that I came here absolutely as an individual. I came here in my capacity as a member of the Institute, and as a man who has spent his life on water power developments, and I will be frank with some of my experiences. I have never lost money to any extent in anything else except water power development. I have had a gentleman in New York tell me that he has had in one autumn sixty-six men who controlled water powers locally and also men from different countries come to him and ask him to help them to raise money for those water power enterprises. Now, there is

one waterpower, not very far from New York, in which the man who controlled it for years was a friend of a friend of mine. This friend happened to call at our office, and he was turned over to me. He had the right to a waterpower and wanted to raise money to finance it, but could not do it. He had been working on it for years and no one would take it up. I had a friend of mine look it up and he said it was no good, that it would not pay, that it did not have a market. The proposition was finally taken to Chicago to people who were somewhat familiar with it. I know they had a difficult time raising the money, people did not want to go into it, they said it did not look good to them. The only place they could go to raise the money was to bankers familiar with the project. In my experience as an engineer I have always seen the pressure come from the other side. I presume there are in New York every year hundreds of men who control complete situations trying to raise the money for them. If you talk to a man who does not know anything about a waterpower, he will not listen to you. It seems to me there has been a great misconception about this matter.

Mr. Dunn has dealt with bankers and knows the difficulties of raising money and in my opinion his paper will add very much to the beneficial result of our meeting here. Mr. Townley's discussion can also be brought to the attention of those who are in any way interested in this very broad and important subject. The financing of water powers, as Mr. Townley said, very truly, is dependent on us. Would any of us invest our money in them. I know a couple of bond brokers who sell bonds in the Mohawk Valley. They go into Amsterdam and offer to sell farmers public utility and water power bonds, and what the farmers pay for the bonds depends on the conditions on which the water power can be installed and operated. The banker goes around and gathers up various opinions and finds out what the people will take the bonds for.

The time is here for a new era of publicity. We are all afraid of the things we do not know—what is behind the doors and what is not brought out is always largely open to suspicion. Take the public into your confidence, work with the public, put the cards right down on the table before the public and show them just what you have.

Oscar T. Crosby: The political problems confronting us in the development of our water powers are these:

First, to what extent shall the authority of the general government, as distinguished from that of the several states, determine the location, physical construction and physical operation of water power plants?

Second, what authority shall control the financial operations of water power companies, including in this phase the control of rates?

Third, assuming these two questions as settled in one way or another, what principle should underlie the control of rates,

of financial organization, of return to capital and of possible acquisition by public authority of private property involved in water power developments? Let us take up these questions in the order I have indicated.

Navigable streams are now fully recognized as being under the jurisdiction of the general government. There is no contention as to the right of that government to determine for or against the placing in such streams of any obstructions whatever. There is very grave contention as to the conditions which may be constitutionally attached, or which in wise policy should be attacked, to a permission given by the general government in any particular case. Should the sole interest of navigation be consulted, with no consideration affecting investment except that the proposed works should not result in navigation costs greater than those which otherwise would fall upon the public?

Should consideration of flood effects, as distinguished from navigation effects, also enter? Should questions of injury and advantage to agricultural lands, through drainage or irrigation be considered by the United States authorities?

In raising these questions, we raise a series of constitutional issues which it would be long and hard to settle. Happily, they need not be settled. If Smith and Jones have overlapping and tangled rights in respect to a tract of land, and if Brown wishes to use the land, then, without waiting for the law's delay, the proposed use of the land may be effected by a joint grant, or by parallel grants from Smith and Jones to Brown. Let Smith be Uncle Sam, let Jones be the State of Ohio, and let Brown be a water power company, and we may proceed to determine the physical questions surrounding any situation in a navigable stream. We may even go further, and thus cover the difficulties as presented by the question as to what *is* a navigable stream, according to the Constitution. The existing legal definitions are such as would let almost any creek into the dignified company of streams, which must recognize in Uncle Sam their overlord.

In my early years, as a young officer of engineers, I examined a "navigable stream (?)" in a buggy. Rubber boots would have done as well, but for the length of the thing.

However extreme the case, we may rest assured that a handsome appropriation will settle most "state's rights" doubts as to the navigability question. But if no appropriation be involved a real issue, affecting validity of permits, remains to be solved. Co-operation of Smith and Jones is the true, practical solution of this, and of the other doubtful points concerning floods, drainage, etc.

But the United States appears in quite a different role than that of overlord and largess-giver, when we regard the public domain in our Western States. Are we dealing here with a sovereign, or with a mere landlord-proprietor, subject to the laws of the local sovereign—the state? In my judgment, that is the true view of the case. But it is a much contested point.

As a citizen of the United States, concerned that all states, east and west, should be in the same relation to lands within their bounds, I should be loath to see any assumption of an *imperium in imperio*, by the general government, because it holds as trustee certain lands in certain Western States. As one easterner, I want to register my cession of title in these lands to the people of the states within which they live. But if this battle cannot be won, then it may at least be compromised by the same principle of co-operation in grants that has just been proposed in the case of navigable streams. But this compromise should go no further than is required for determining the physical elements,—the construction elements—of each case.

When we meet the matter of financial control in all its aspects, I am firmly convinced that the states alone should determine. Even if the courts should decide that the general government has a right to enter this field, yet would I contend that as a matter of policy it should not enter it.

There are good men in the Washington bureaucracy, but there are few efficient bureaucracies in all the world. Can men be established in this city to administer wisely through subordinates the distant affairs of a Californian hydroelectric company? Will it be a bearable burden if an operator in Oregon must communicate with Washington in all those intimate ways which have been made familiar to us by the Public Utility Commissions of our states? Is the burden not now heavy enough when recourse must be had in so many matters to boards sitting in state capitols? And shall we have in the same state one control for steam plant generation, and another for water generation of electricity? What confusion! What discouragement!

Let us hope that this madness of centralization of control in Washington will pass.

Let us now consider the *principles* of control, without respect to the question as to which of our dual sovereignties is to exercise that control.

Men invest money in public utilities, not in order to charge particular rates for service, but in an effort to earn a return on the capital invested. That is the objective. A just and reasonable rate is a rate that will cause money and energy to flow into the enterprise which performs a given service, whether that service be the sale of electric energy or the sale of bread or shoes.

Then since it is right that there should be control of monopolies and since public utilities are necessarily monopolies (in the long run and in respect to at least some part of their clientele), let this control express itself in contracts relating in plain terms and in specific figures the return on capital. Rates may then be left to those who conduct the operations, subject, of course, to the usual common law rule against discriminatory practises.

These contracts as to return on capital may vary very widely from case to case; they should generally be on a sliding scale basis, providing lower returns in proportion to assured success,

but they should be specific and clear. Let us get away from the unreasonable "rule of reasonableness"—misrule of unreasonableness—which now leaves rates and returns almost wholly to the guess of commissioners. Most of them are good men, but good men are not always wise men, and even wise men should not be left to decide vast property interests without guiding principles which put all parties on notice as to their rights. Let us recognize that the inventor has destroyed the old common law rule of reasonableness, which was the rule of custom. Now the ferment of invention has, for nearly a hundred years, prevented custom from taking a "permanent set," and this ferment is destined to continue. Customary rates will not be established. Contract rates may be fixed to a limited extent, chiefly as maxima. But there is no difficulty in *fixing returns* to *capital* on a sliding scale in each contract for a public service.

And as to the final chapter, the possible taking over of a property by the public, we hear far too much about it. The old law of eminent domain seems to be forgotten. No "perpetual franchise" can hold against the right of the government to take anything it wants. No fixed term franchise can hold against that right. A grant of today may be taken tomorrow. But private property must be paid for if thus taken. Now, the terms of payment may be fixed far in advance, or may be left to a jury at any time. If we had contracts fixing possible (not guaranteed) returns on capital, those contracts interpreted in the light of actual results obtained by operation, and with known investment figures, would render relatively simple the now fearsome task of fixing a condemnation value.

I append a copy of the bill proposed by me some years ago to cover the matter of permits for water-power construction.

(See proposed bill referred to by Mr. Crosby in hearing before National Waterways Commission, Washington, November, 1911, pages 136 and 137.)

Gano Dunn: I want to do service to a friend and to say to the Honorable Congressman that he understood Mr. Baekeland exactly the reverse of what Mr. Baekeland meant about Congress. Mr. Baekeland's experience has been the same as that of all the rest of us when we came down here—we have been received very courteously and listened to with such attention that we have been made to feel that every member of Congress or the committee we have gone before has been extremely desirous of drawing out all the facts. This has caused us to revise some of our former false opinions to the contrary.

I would like to read to the Congressmen and others who may be interested, the official policy of the American Institute of Electrical Engineers in regard to these matters, especially in view of his suggestion that we develop and bring out a bill for specific suggestions as to how water-powers should be handled: "The governing body of the Institute has continued its special

committee (on water power) in consequence of these successive invitations in view of the apparent appreciation on the part of the government that the services rendered by the American Institute of Electrical Engineers were scientific and professional and not commercial or political, that its committees dealt with fundamental engineering and economic principles of hydro-electric development that were outside the field of controversy, and that the function of the Institute being scientific and professional and not commercial or political, its status was one involving a high degree of disinterestedness in respect to matters on which its technical advice was sought."

Mr. Baekeland referred to an address which I had the honor of making before the Washington Society of Engineers some time ago, in which he mistakenly reported me as saying that engineers ought never to mix in politics and other things. What I said was that in the appointment of the Naval Advisory Board, I believed for the first time in history the engineer, as such, had been invited to sit on the bench of Government with the statesman and co-operate with and help him; but I also said that the engineer should never go so far as to think that he can take the place of the statesman. The function is different and requires a different kind of man. The engineer is not big enough to do both things, and if we appointed an engineer as Secretary of State, our diplomacy would be likely to suffer. Therefore, I feel that we should stay in our own province as technical experts, and advise about the things we know, we should go before the various committees of Congress and answer inquiries about these things, but it is to them we should leave the other questions of what bills should be drawn and what kind of political bodies should be created to do the regulating and administering of the affairs of the government generally. Something toward this aim is what we hoped to accomplish in organizing this meeting here for the discussion of water-powers.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

THE RELATION OF PURE SCIENCE TO INDUSTRIAL RESEARCH

PRESIDENT'S ADDRESS

BY J. J. CARTY

IT IS not strange that many years ago Huxley, with his remarkable precision of thought and his admirable command of language, should have indicated his dissatisfaction with the terms "pure science" and "applied science", pointing out at the same time that what people call "applied science" is nothing but the application of pure science to particular classes of problems. The terms are still employed, possibly because, after all, they may be the best ones to use, or perhaps our ideas, to which these expressions are supposed to conform, have not yet become sufficiently definite to have called forth the right words.

It is not the purpose of this address, however, to suggest better words or expressions, but rather to direct attention to certain important relations between purely scientific research and industrial scientific research which are not yet sufficiently understood.

Because of the stupendous upheaval of the European war with its startling agencies of destruction—the product of both science and the industries—and because of the deplorable unpreparedness of our own country to defend itself against attack, there has begun a great awakening of our people. By bringing to their minds the brilliant achievements of the membership of this Institute in electric lighting and power and communications and by calling their attention to the manifold achievements of the members of our sister societies in mechanical and mining and civil engineering, and the accomplishments of our fellow-workers, the industrial chemists, they are being aroused to the vital importance of the products of science in the national defense.

Arising out of this agitation comes a growing appreciation of the importance of industrial scientific research, not only as an

aid to military defense but as an essential part of every industry in time of peace.

Industrial research, conducted in accordance with the principles of science, is no new thing in America. The department which is under my charge, founded nearly forty years ago to develop, with the aid of scientific men, the telephone art, has grown from small beginnings with but a few workers to a great institution employing hundreds of scientists and engineers, and it is generally acknowledged that it is largely owing to the industrial research thus conducted that the telephone achievements and development in America have so greatly exceeded those of other countries.

With the development of electric lighting and electric power and electric traction which came after the invention of the telephone, industrial scientific research laboratories were founded by some of the larger electrical manufacturing concerns and these have attained a world-wide reputation. While vast sums are spent annually upon industrial research in these laboratories, I can say with authority that they return to the industries each year improvements in the art which, taken all together, have a value many times greater than the total cost of their production. Money expended in properly directed industrial research, conducted on scientific principles, is sure to bring to the industries a most generous return.

While many concerns in America now have well organized industrial research laboratories, particularly those engaged in metallurgy and dependent upon chemical processes, the manufacturers of our country as a whole have not yet learned of the benefits of industrial scientific research and how to avail themselves of it.

I consider that it is the high duty of our Institute and of every member composing it, and that a similar duty rests upon all other engineering and scientific bodies in America, to impress upon the manufacturers of the United States the wonderful possibilities of economies in their processes and improvements in their products which are opened up by the discoveries in science. The way to realize these possibilities is through the medium of industrial research conducted in accordance with scientific principles. Once it is made clear to our manufacturers that industrial research pays, they will be sure to call to their aid men of scientific training to investigate their technical problems and to improve their processes. Those who are the first to avail

themselves of the benefits of industrial research will obtain such a lead over their competitors that we may look forward to the time when the advantages of industrial research will be recognized by all.

Industrial scientific research departments can reach their highest development in those concerns doing the largest amount of business. While instances are not wanting where the large growth of the institution is the direct result of the care which it bestowed upon industrial research at a time when it was but a small concern, nevertheless conditions to-day are such that without cooperation among themselves the small concerns cannot have the full benefits of industrial research, for no one among them is sufficiently strong to maintain the necessary staff and laboratories. Once the vital importance of this subject is appreciated by the small manufacturers many solutions of the problem will promptly appear. One of these is for the manufacturer to take his problem to one of the industrial research laboratories already established for the purpose of serving those who cannot afford a laboratory of their own. Other manufacturers doing the same, the financial encouragement received would enable the laboratories to extend and improve their facilities so that each of the small manufacturers who patronizes them would in course of time have the benefit of an institution similar to those maintained by our largest industrial concerns.

Thus, in accordance with the law of supply and demand, the small manufacturer may obtain the benefits of industrial research in the highest degree and the burden upon each manufacturer would be only in accordance with the use he made of it, and the entire cost of the laboratories would thus be borne by the industries as a whole, where the charge properly belongs. Many other projects are now being considered for the establishment of industrial research laboratories for those concerns which cannot afford laboratories of their own, and in some of these cases the possible relation of these laboratories to our technical and engineering schools is being earnestly studied.

Until the manufacturers themselves are aroused to the necessity of action in the matter of industrial research there is no plan which can be devised that will result in the general establishment of research laboratories for the industries. But once their need is felt and their value appreciated and the demand for research facilities is put forth by the manufacturers themselves, research laboratories will spring up in all our great

centers of industrial activity. Their number and character and size, and their method of operation and their relation to the technical and engineering schools, and the method of their working with the different industries, are all matters which involve many interesting problems—problems which I am sure will be solved as they present themselves and when their nature has been clearly apprehended.

In the present state of the world's development there is nothing which can do more to advance American industries than the adoption by our manufacturers generally of industrial research conducted on scientific principles. I am sure that if they can be made to appreciate the force of this statement, our manufacturers will rise to the occasion with all that energy and enterprise so characteristic of America.

So much has already been said and so much remains to be said urging upon us the importance of scientific research conducted for the sake of utility and for increasing the convenience and comfort of mankind, that there is danger of losing sight of another form of research which has for its primary object none of these things. I refer to pure scientific research.

In the minds of many there is confusion between industrial scientific research and this purely scientific research, particularly as the industrial research involves the use of advanced scientific methods and calls for the highest degree of scientific attainment. The confusion is worse because the same scientific principles and methods of investigation are frequently employed in each case and even the subject matter under investigation may sometimes be identical.

The misunderstanding arises from considering only the subject matter of the two classes of research. The distinction is to be found not in the subject matter of the research, but in the motive.

The electrical engineer, let us say, finding a new and unexplained difficulty in the working of electric lamps, subjects the phenomenon observed to a process of inquiry employing scientific methods, with a view to removing from the lamps an objectionable characteristic. The pure scientist at the same time investigates in precisely the same manner the same phenomenon, but with the purpose of obtaining an explanation of a physical occurence, the nature of which cannot be explained by known facts. Although these two researches are conducted in exactly the same manner, the one nevertheless comes under the head of

industrial research and the other belongs to the domain of pure science. In the last analysis the distinction between pure scientific research and industrial scientific research is one of motive. Industrial research is always conducted with the purpose of accomplishing some utilitarian end. Pure scientific research is conducted with a philosophic purpose, for the discovery of truth, and for the advancement of the boundaries of human knowledge.

The investigator in pure science may be likened to the explorer who discovers new continents or islands or hitherto unknown territory. He is continually seeking to extend the boundaries of knowledge.

The investigator in industrial research may be compared to the pioneers who survey the newly discovered territory in the endeavor to locate its mineral resources, determine the extent of its forests, and the location of its arable land, and who in other ways precede the settlers and prepare for their occupation of the new country.

The work of the pure scientists is conducted without any utilitarian motive, for, as Huxley says, "that which stirs their pulses is the love of knowledge and the joy of discovery of the causes of things sung by the old poet—the supreme delight of extending the realm of law and order ever farther towards the unattainable goals of the infinitely great and the infinitely small, between which our little race of life is run." While a single discovery in pure science when considered with reference to any particular branch of industry, may not appear to be of appreciable benefit, yet when interpreted by the industrial scientist, with whom I class the engineer and the industrial chemist, and when adapted to practical uses by them, the contributions of pure science as a whole become of incalculable value to all the industries.

I do not say this because a new incentive is necessary for the pure scientist, for in him there must be some of the divine spark and for him there is no higher motive than the search for the truth itself. But surely this motive must be intensified by the knowledge that when the search is rewarded there is sure to be found, sooner or later, in the truth which has been discovered, the seeds of future great inventions which will increase the comfort and convenience and alleviate the sufferings of mankind.

By all who study the subject, it will be found that while the discoveries of the pure scientist are of the greatest importance to the higher interests of mankind, their practical benefits, though certain, are usually indirect, intangible or remote.

Pure scientific research unlike industrial scientific research can not support itself by direct pecuniary returns from its discoveries.

The practical benefits which may be immediately and directly traced to industrial research, when it is properly conducted, are so great that when their importance is more generally recognized industrial research will not lack the most generous encouragement and support. Indeed, unless industrial research abundantly supports itself, it will have failed of its purpose.

But who is to support the researches of the pure scientist, and who is to furnish him with encouragement and assistance to pursue his self-sacrificing and arduous quest for that truth which is certain as time goes on to bring in its train so many blessings to mankind? Who is to furnish the laboratories, the funds for apparatus and for traveling and for foreign study?

Because of the extraordinary practical results which have been attained by scientifically trained men working in the industrial laboratories and because of the limited and narrow conditions under which many scientific investigators have sometimes been compelled to work in universities, it has been suggested that perhaps the theater of scientific research might be shifted trom the university to the great industrial laboratories which have already grown up or to the even greater ones which the future is bound to bring forth. But we can dismiss this suggestion as being unworthy.

Organizations and institutions of many kinds are engaged in pure scientific research and they should receive every encouragement, but the natural home of pure science and of pure scientific research is to be found in the university, from which it cannot pass. It is a high function of the universities to make advances in science, to test new scientific discoveries and to place their stamp of truth upon those which are found to be pure. In this way only can they determine what shall be taught as scientific truth to those who, relying upon their authority, come to them for knowledge and believe what they teach.

Instead of abdicating in their favor, may not our universities, stimulated by the wonderful achievements of these industrial laboratories, find a way to advance the conduct of their own pure scientific research, the grand responsibility for which rests upon them. This responsibility should now be felt more heavily than ever by our American universities, not only because the tragedy of the great war has caused the destruction of European institutions of learning, but because even a worse thing has

happened. So great have been the fatalities of the war that the universities of the old world hardly dare to count their dead.

But what can the American universities do, for they, like the pure scientists, are not engaged in a lucrative occupation. Universities are not money-making institutions, and what can be done without money?

There is much that can be done without money. The most important and most fundamental factor in scientific research is the mind of a man suitably endowed by nature. Unless the scientific investigator has the proper genius for his work, no amount of financial assistance, no apparatus or laboratories, however complete, and no foreign travel and study however extensive, will enable such a mind to discover new truths or to inspire others to do so. Judgment and appreciation and insight into character on the part of the responsible university authorities must be applied to the problem, so that when the man with the required mental attributes does appear he may be appreciated as early in his career as possible. This is a very difficult thing to do indeed. Any one can recognize such a man after his great achievements have become known to all the world, but I sometimes think that one who can select early a man who has within him the making of the scientific discoverer must have been himself fired with a little of the divine spark. Such surely was the case with Sir Humphrey Davy, himself a great discoverer, who, realizing the fundamental importance of the man in scientific discovery, once said that Michael Faraday, whose genius he was prompt recognize, constituted his greatest discovery.

I can furnish no formula for the identification of budding genius and I have no ready-made plan to lay before the universities for the advancement of pure scientific research. But as a representative of engineering and industrial research, having testified to the great value of pure scientific research, I venture to suggest that the university authorities themselves might well consider the immense debt which engineering and the industries and transportation and communications and commerce owe to pure science, and to express the hope that the importance of pure scientific research will be more fully appreciated both within the university and without, for then will come—and then only—that sympathetic appreciation and generous financial support so much needed for the advancement of pure scientific research in America.

While there are many things—and most important things—which the universities can do to aid pure science without the employment of large sums of money, there are nevertheless a great many things required in the conduct of pure scientific research which can be done only with the aid of money. The first of these I think is this:

When a master scientist does appear and has made himself known by his discoveries, then he should be provided with all of the resources and facilities and assistants that he can effectively employ, so that the range of his genius will in no way be restricted for the want of anything which money can provide.

Every reasonable and even generous provision should be made for all workers in pure science, even though their reputations have not yet become great by their discoveries, for it should be remembered that the road to great discoveries is long and discouraging and that for one great achievement in science we must expect numberless failures.

I would not restrict these workers in pure science to our great universities, for I believe that they should be located also at our technical schools, even at those with the most practical aims. In such schools the influence of a discoverer in science would serve as a balance to the practical curriculum and familiarize the student with the high ideals of the pure scientist and with his rigorous methods of investigation. Furthermore, the time has come when our technical schools must supply in largely increasing numbers men thoroughly grounded in the scientific method of investigation for the work of industrial research.

Even the engineering student, who has no thoughts of industrial research, will profit by his association with the work of the pure scientist, for if he expects ever to tread the higher walks of the engineering profession he must be qualified to investigate new problems in engineering and devise methods for their solution and for such work a knowledge of the logical processes of the pure scientist and his rigorous methods of analyzing and weighing evidence in his scrupulous search for the truth will be of the greatest value.

Furthermore, the engineering student should be taught to appreciate the ultimate great practical importance of the results of pure scientific investigation and to realize that pure science furnishes to engineering the raw material, so to speak, which he must work into useful forms. He should be taught that after graduation it will be most helpful to him and even necesary, if

he is to be a leader, to watch with care the work of the pure scientist and to scrutinize the reports of new scientific discoveries to see what they may contain that can be applied to useful purposes and more particularly to problems of his own which require solution. There are many unsolved problems in applied science, to-day which are insoluble in the present state of our knowledge, but I am sure that in the future, as has so often happened in the past, these problems will find a ready solution in the light of pure scientific discoveries yet to be made. When thus regarded the work of the pure scientist should be followed with most intense interest by all of those engaged in the application of science to industrial purposes. Acquaintance, therefore with the pure scientist, with his methods and results, is of great importance to the student of applied science. I believe that there is need of a better understanding of the relations between the pure scientist and the applied scientist and that this understanding would be greatly helped by a closer association between the pure scientist and the students in the technical schools.

While I have drawn a valid distinction between the work of the two, they nevertheless have much in common. Both are concerned with the truth of things, one to discover new truths and the other to apply these truths to the uses of man. While the object of the engineer is to produce from scientific discoveries useful results, these results are for the benefit of others. They are dedicated to the use of mankind and, as is the case with the pure scientist, they should not be confused with the pecuniary compensation which the engineer himself may receive for his work for this compensation is slight, often infinitesimally so, compared with the great benefits received by others. Like the worker in pure science, the engineer finds inspiration in the desire for achievement and his real reward is found in the knowledge of the benefits which others receive from his work.

There are many other things which might be discussed concerning the conduct of pure scientific research in our universities and technical schools, but enough has been said to make it plain that I believe such work should be greatly extended in all of our American universities and technical institutions. But where are the universities to obtain the money necessary for the carrying out of a grand scheme of scientific research? It should come from those generous and public spirited men and women who desire to dispose of their wealth in a manner well calculated to advance the welfare of mankind, and it should come from the industries themselves, which owe such a heavy debt to science.

While it cannot be shown that the contribution of any one manufacturer or corporation to a particular purely scientific research will bring any return to the contributor or to others, it is certain that contributions by the manufacturers in general and by the industrial corporations to pure scientific research as a whole will in the long run bring manifold returns through the medium of industrial research conducted in the rich and virgin territory discovered by the scientific explorer.

It was Michael Faraday, one of the greatest of the workers in pure science, who in the last century discovered the principle of the dynamo electric machine. Without a knowledge of this principle discovered by Faraday the whole art of electrical engineering as we know it to-day could not exist and civilization would have been deprived of those inestimable benefits which have resulted from the work of the members of this Institute.

Not only Faraday in England, but Joseph Henry in our own country and scores of other workers in pure science have laid the foundations upon which the electrical engineer has reared such a magnificent structure.

What is true of the electrical art is also true of all of the other arts and applied sciences. They are all based upon fundamental discoveries made by workers in pure science, who were seeking only to discover the laws of nature and extend the realm of human knowledge.

By every means in our power, therefore, let us show our appreciation of pure science and let us forward the work of the pure scientists, for they are the advance guard of civilization. They point the way which we must follow. Let us arouse the people of our country to the wonderful possibilities of scientific discovery and to the responsibility to support it which rests upon them, and I am sure that they will respond generously and effectively. Then I am confident that in the future the members of this Instutite, together with their colleagues in all of the other branches of engineering and applied science, as well as the physician and surgeon, by utilizing the discoveries of pure science yet to be made, will develop without number marvelous new agencies for the comfort and convenience of man and for the alleviation of human suffering. These, gentlemen, are some of the considerations which have led me here in my presidential address to urge upon you the importance of a proper understanding of the relations between pure science and industrial research.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

STANDARDIZATION

BY C. LE MAISTRE

ALLOW me to commence these remarks by saying how deeply sensible I am of the honor of addressing this representative gathering of American electrical engineers. Thoughtful Europeans, as Lord Bryce well said, have begun to realize the increasing influence of this vast country in the affairs of the world, and the splendor of the part reserved to you in the development of civilization. A brief visit to your hospitable shores has been an inspiration and has enabled me to appreciate, in some small measure, the freedom of your thought, and the breadth of your conceptions. Such is the grandeur of your outlook that I can but echo what was so beautifully expressed by one of the orators at the recent Harvard commencement exercises, namely, that the world needs you and the world will heed you if you but acquit yourselves as men!

So much has been written regarding standardization, and the art has become so necessary to progress, and is so familiar to many of you, that I cannot hope to do more than focus your ideas on a few of the more important aspects of the subject. I shall also try to bring into prominence some of the points connected with the development of engineering standards in Great Britain, which I hope may be of interest, more especially as in order to minimize overlapping and obviate piecemeal methods, the question of co-ordinating the various individual methods in one homogeneous body is occupying the serious attention of competent authorities in this country.

In matters electrical, national and international standardization are so intimately connected that it is scarcely possible to speak of the one without discussing the other. Indeed, international standardization, a barbarous term it is true, but a difficult one to supplant, would seem to be the natural development from the experience gained in the practical application of national standards.

It was stated on one occasion, I remember, that the earliest

record of standardization was to be found in the introduction of the Greek alphabet initiated by Xerxes and which was refused by China and Russia. However that maybe, the most notable step in the realization of engineering standards, in so far as Great Britain is concerned, was in 1841, when Sir Joseph Whitworth introduced his standard screw thread. When urging the necessity for standardization, he illustrated his argument by mentioning that candles and candle-sticks were in use in almost every house, and nothing could be more convenient than for the candles to fit accurately into the sockets of the candle sticks, which they seldom did. The lesson taught by his illustration lies at the root of standardization and necessarily carries with it disadvantage to the few for the advantage to the many.

Then we come to the Standards Committee of this Institute, of which Prof. Crocker was the first Chairman, which reported on electrical standardization in 1898. The splendid pioneer work accomplished by that committee has been an incentive to many others and whatever form the proposed central organization may take, the Standards Committee of this Institute will doubtless retain intact its distinctive character whilst supplementing and extending its activities.

Several factors, including keen competition from outside, the legitimate demands of labor for a higher standard of living, coupled with the desire of capital for a better return, have compelled the electrical, in common with the whole engineering industry, to introduce modern order and system into all its methods of production. Former individualistic methods have been forced to give way to co-ordination and collective effort. It is, in fact, co-operation which gives the highest value to individual effort. This, if voluntary and not compulsory, will help to maintain quality.

Now, these improvements which have already resulted in marked benefits, must not only be maintained, but continually added to if the full advantages are to be reaped. Inevitably the necessity of standards to which the products of the workshops may be referred, has manifested itself just as much as fixed standards of weights and measures.

Of course, the individual gain, economically, in private workshop standardization is acknowledged great to the producer for it tends towards interchangeability of working parts, lessens maintenance charges and stores; crystallization, however, which would tend to impede and in some cases stultify progress must

be jealously guarded against if monopolies are to be avoided and the purchaser is not to be deprived of the benefit of competitive effort and inventive genius. If, therefore, through some comprehensive centralized body, the users and producers alike can be persuaded to accept an agreed standard, the community interests of buyer and seller are thereby realized and a high average efficiency secured. Generally speaking, satisfactory standardization, whether national or international, has usually been arrived at not by one section of the community imposing its opinions on the other, but rather as the result of co-operative action on the part of all concerned.

Experience has clearly shown that such procedure does not lower the standard, but if anything tends rather to raise it. It reflects, in effect, the consensus of opinion as to what constitutes best modern practise. Such standardization is only arrived at by common consent of the governed who take full part in the discussions and in the initiating and working out of the actual details of the specifications to be recommended for public use. This is one of the chief reasons why the work of the Engineering Standards Committee of Great Britain is so widely adopted—because of the utmost care which is taken, at the very outset, to insure that all who have or could possibly have any interest in the proposed standardization shall have an adequate representation on the Committee drafting the recommendation. This representation is usually effected through the recognized societies and associations of the particular engineers or trades concerned. Such methods register the views of the experts in manufacture as well as those intimately acquainted with the conditions under which machinery and apparatus are employed in every day service.

Undoubtedly, mutual concession and ultimate agreement between the parties interested tend towards uniformity of practise, avoidance of waste, elimination of harsh and unnecessary conditions, and last, but by no means least, bring about a feeling of mutual confidence, such as could not be realized by isolated action on the part of either, however honorable and straightforward it may be.

Again, though much time and labor be occupied in preparing such standard specifications, additions and emendations demanded by experience and new developments must be provided for, and consequently, the specifications must be reviewed annually and thus eliminate undesirable stereotyping of pro-

cedure. Such revisions must also be promptly and efficiently dealt with. The standards should have no other authority than that of commom consent. In fact, it is public opinion which gives them their dynamic force, and all progress would be arrested if there was a possibility of their being enacted into statutory law.

The initiation in 1901 of the British Engineering Standards Committee, the greatest private voluntary effort of the kind, is due to Sir John Wolfe Barry, K. C. B., whose name is a household word amongst British engineers. His commanding influence in the engineering world, and the deep respect in which he is held by the whole profession has probably been the greatest factor in bringing this organization to its present unassailable position. It had a small beginning, but has increased in scope and efficiency till today its influence is felt and its specifications acknowledged and worked to throughout practically the whole of the Empire. Its main committee, or Senate, is composed of the official representatives of the five leading engineering institutions; to this committee falls the whole administration of the work, the raising of the necessary funds, the controlling of the expenditure and the ratification of all reports and specifications presented by the various sectional committees prior to publication. The sectional committees are instituted by this main committee which appoints the respective chairmen. Under this main committee there are some 80 sectional sub-committees and small panels, the membership being between 500 and 600. The sectional committees consist of representatives of the various government departments, consulting engineers, manufacturers and users, as well as representatives of the technical societies and trade associations interested in or affected by the subjects under consideration. The sectional committees, and in some cases the sub-committees, decide the broad lines upon which the specifications are to be drawn up and then delegate the working out of the preliminary details to a sub-committee or panel. If necessary, evidence is taken, the advice of experts is sought, and in this way all parties are consulted and have a proper voice in the initial proposals, thus avoiding much subsequent friction which might otherwise occur.

The specifications of the committee find an increasingly wide adoption, being more and more substituted for the various government and municipal specifications hitherto employed. They deal with the main technical clauses, leaving questions of contact to be dealt with by the purchaser.

The electrical section of the committee, which forms an important part of the whole, is under the able chairmanship of Sir John Snell. It has recently been entirely reorganized, and is now *ipso facto* the British National Committee of the International Electrotechnical Commission, or the I. E. C. as it is called. Thus the national and international interests of the British electrical industry are under one organization with increase of efficiency in every way. Dr. R. T. Glazebrook, C. B., is the chairman of the committee when I. E. C. matters are under discussion.

In drawing up industrial standards covering electrical machinery and apparatus, experimental investigations frequently become necessary in order to establish the facts underlying the principles involved, and it is in this connection that the National Physical Laboratory has been and is so conspicuously useful to the Standards Committee. It is in effect our official testing bureau, and our ultimate authority, and it acts in an advisory capacity in practically all the work. The success of the British Standards Committee is due in large measure to the energy, foresight and ability of Mr. Leslie Robertson, the Chief Secretary, whose geniality and intimate knowledge of men and affairs have enabled him to cope successfully with problems many another would have hesitated to undertake. Going on a government mission he perished with Lord Kitchener on June 6th last, an irreparable loss to us all.

The commerce of the world, due to the wondrous development of communication, has, one might almost say, in spite of the artificial barriers set up by the different nations, become more and more international. It is, of course, inevitable that the standardization rules for electrical machinery in use in the various countries should differ in detail because conditions of manufacture necessarily differ and so influence the rules. Yet the method of ascertaining the actual rating of a machine, paper rating one might almost call it, so important to the prospective purchaser, especially when separated from the maker by long distances, as is often the case, should surely be identical in all countries, since it depends on the physical and mechanical properties of the machine, and is not a question of geographical position. This is peculiarly the work of the I. E. C.

Theory and practise are perhaps more closely allied in electrical engineering than in any other applied science, and it is therefore, important in the application to industrial purposes

of the laws of electrotechnics, that the rules which form the basis of technical specifications and consequently of commercial contracts, should be as free as possible from ambiguity and complications, yet at the same time sufficiently definite and comprehensive to insure a satisfactory means of comparison between the machine supplied and the standard.

The problem is, however, more intricate than that of dealing with simple pieces of mechanism, for it involves the consideration of the peculiar properties of the materials forming the essential portions of the machine. For instance, the conductivity of the copper or the permeability of the iron can be measured with substantial accuracy and, what is more important still, without the portion tested being destroyed or damaged. The mechanical strength of the materials also can be estimated with sufficient accuracy from the result of definite and easily carried out tests on samples of the materials, with almost complete assurance that the bulk material will have the same properties and therefore behave in the same way as the samples tested. These particular properties are, in fact, of such a nature that they can be specified with precision, and moreover, are not appreciably affected by the elements of time. When the question of the insulating materials, however, is considered, the problem is of course, very different, and one can but acknowledge that owing to their inherent properties, the insulating materials employed at present, come into an entirely different category. They are governed by no well-defined laws, as in the case of the copper and iron, their properties are variable and alter largely for very small changes in the conditions of manufacture, as well as those under which they are employed in the completed machine. The resistance they offer to the passage of the current constantly changes, and tests on samples are, therefore, not very satisfactory, as varying the length of the test may give results differing considerably in magnitude. One of the most important problems, therefore, is the settling of the limits which it is considered necessary to impose in order to insure that the principal causes of destruction of the insulating materials, the heating combined with the time element, shall be kept well within safe limits.

A clear distinction exists between an "international standard of quality" and an "international rating." The international acceptance of the former has already been brought about by the adoption, by the I. E. C., at its Berlin meeting in September,

1913, of certain limits of observable temperature applying to the materials in general use today. But these limits do not offer a means of comparing directly machines from various sources, since they would not necessarily have the same temperature rise. No international decision has yet been arrived at in regard to the value of the cooling-air temperature to be associated with the upper limits already adopted, the commission wisely preferring to adhere to its rule of not taking action on any important question except on a four-fifths majority of the countries registering their votes. The wisdom of this procedure has been amply justified on more than one occasion, and although the advent of the war has unfortunately resulted, in so far as international standardization is concerned, in what might be termed a state of suspended animation, there is every reason to anticipate that the delay thus enforced will not adversely affect the solution of this particular problem.

However, there are very good grounds for hoping that the temperature rise recognized as standard in America and Great Britain will ultimately be accepted throughout the world.

It is evident also that the standardization rules in use in the various countries will tend to grow less divergent in proportion as the work of the I. E. C. progresses, and although the international rules are not intended to supplant those employed locally, they cannot fail, when issued, to be of material assistance to buyers and sellers of all nationalities. In addition to, or rather collaterally with, the rating of machinery, the I. E. C., through properly constituted special committees, has under consideration several other matters which come under the general heading of nomenclature and symbols. The work accomplished, so far, in these directions, may by some, be considered somewhat academical, but it should not be overlooked that international symbols, if widely adopted as they deserve to be, will greatly assist in the reading of foreign technical works, and that international agreement in regard to nomenclature, immensely difficult as it is, and calling for so much personal sacrifice of long-cherished conditions, will be of the greatest value to the industry generally. Also the subject of graphical symbols for electrical plans now being studied will be of considerable assistance in foreign tenders. Experience shows that the utmost caution is necessary in all international questions, and that nothing is to be gained by forcing a vote on a point not yet ripe for decision. One may hope with confidence that when

peace reigns once more in distracted Europe, industry will be more than rehabilitated, and the electricians of the world fully appreciating, as they have, the potentialities of such co-operation, will continue their work so well begun.

I cannot close this brief review without paying a tribute of love and respect to the father of the I. E. C., Col. R.E. Crompton, C. B., its Honorary Secretary, to whose enthusiasm and ceaseless energy the commission owes its very inception. He has been a tower of strength at all times, and has ever been ready with the counsel of his ripe experience to help and encourage us through all our vicissitudes. May he long be spared to us!

I should like also to record my appreciation of the invaluable assistance of the American Section of the I. E. C., which the central office has so uninterruptedly enjoyed. To Dr. Mailloux, with his wonderful linguistic ability, we owe a debt it is impossible to repay. In the early stages of the movement, it was owing to the perfect ease with which he was able to explain knotty points in several languages, almost without realizing in which he was speaking, that the many difficulties connected with the launching of such an enterprise were successfully smoothed away. To Dr. Kennelly, too, I owe much for the kindly help and advice he has always so generously given me. Indeed, in times of difficulty, the American Section has never been appealed to in vain.

Laboring thus in the fullest degree for the advancement of the electrical industry of the world, it will be this close co-operation which will win the day, due, not so much to any particular individual, but rather, as Kipling says, "to the everlasting team-work of every blooming soul."

DISCUSSION ON "STANDARDIZATION" (LE MAISTRE) CLEVELAND, OHIO, JUNE 27, 1916.

Clayton H. Sharp: We are, indeed, very fortunate to have Mr. le Maistre with us here today. He has told us something about the work and organization of the Engineering Standards Committee of Great Britain, and of the I. E. C., but, naturally, did not say anything to us about what I might call the real *deus ex machina* of international standardization, and that is Mr. le Maistre himself. If it had not been for his extraordinary genius in diplomacy, in turning the sharp angles, in smoothing down the ruffled feelings, in finding the way out, in working with entire self-effacement, and self-forgetfulness, with the major end in view, if it had not been for the wonderful work on the part of Mr. le Maistre, the success of the entire movement would have been very questionable, indeed.

Those of us who have been to the other side to attend the meetings of the I. E. C. and of its committees, have formed a very great affection for him, and the utmost confidence in his far-sightedness, and above all, in his fair-mindedness. Now that he has come over to this country, the contact between the work of the British Committee of the International Electrotechnical Commission and our own Committee will undoubtedly be established even more closely than before, and we know we have in Mr. le Maistre a thoroughly reliable foreign connection, a go-between, if you please, whereby the concordance of the work in this country with the work in Great Britain will be assured, since he will act to each committee as an interpreter of the work of the other. We, therefore, ought to thank him for coming, and we ought to thank his broad-minded chiefs on the other side who have sent him. I am sure he will go back with the heartiest good wishes of all of us who have met him here.

Farley Osgood: I cannot say too many kind things about our English friend, Mr. le Maistre. He came here a few weeks ago, unknown personally to most of us, although well known by reputation, and he at once was a help to us in our standardization work. His assistance at the Chicago conference of the Bureau of Standards, in connection with the Safety Code, was very great and his clear explanation of the English methods of caring for this kind of work very materially assisted in our discussion at that time, and all felt that we were fortunate to have had a visit from him at this most opportune moment.

C. P. Steinmetz: I have little to add, except to say that as a member the first Standards Committee which was organized here in 1897, and repeated the next year, and as a member of all the succeeding Standards Committees and all the National Electrical Committees, until the last year, when naturally the younger generation, our pupils, took over the work, I have always been very much interested in the work of national and international standardization, though I must confess that when international standardization was started I very much doubted

the feasibility of accomplishing many of the results aimed at, due to the difficulty of getting practically unanimous agreement, which was necessary, between all the nations, but I must confess I was greatly surprised by the relatively large amount of work accomplished.

How this was done I have only in the last day or two been able to realize, by having a chance to discuss the matter with Mr. le Maistre, and I then realized that in this work, as in many others, the result was to a very large extent the personal accomplishment of one who devoted all of his time and energy to the purpose.

Mr. le Maistre says that the work of international standardization is now unfortunately in a state of suspended animation; that is true, but during these days the world is being impulsively driven into shape for co-operation, and all standardization is based on co-operation. When this unfortunate war ends, and the nations wake up again, after finding themselves very much changed, the old idea of every one for himself will be seen to have vanished, and there will be a greater realization of the necessity of co-operation for the mutual welfare. We may well imagine that these few days of suspended animation are not lost, but that the work of international standardization will proceed with increasing rapidity and it will more than make up for the lost time, as soon as these present conditions pass.

C. le Maistre: So many kind things have been said of me by so many people that it would take a very long time if I tried to thank each one personally.

My visit here has, I have said repeatedly, been to me an inspiration. I have seen the large way in which you view the problems, I have seen the co-operative spirit so alive here; and as to the kindnesses which have been shown me by everybody, by the manufacturers, the large corporations as well as the smaller manufacturers, who have done so much for my physical comfort as well as for my mental instruction, I can only say I go back to London with a feeling that I really have been accepted as one of your family.

Words are very poor conveyers of thought, and I could not really express to you these feelings of unspeakable gratitude I have for having had the privilege of coming to America and of knowing something of your institutions, and of meeting so many men, so eminent in our profession, but, at the risk of repeating myself, I say that I hope that, at least in some cases, that these friendships will not be like the high-tension spark, but more like the continuous current.

Due to the rapidity with which communications are increasing in proficiency, the world is becoming more and more one nation, and it is by these meetings that we are gradually becoming more highly cosmopolitan in the truest sense of the word. We get our rough edges knocked off and begin to appreciate other people. I am sure my own Committee will appreciate very highly, indeed, the reception which their delegate has received here, and the very substantial co-operation that there has been between our nations.

I can say that I have so many friends here that I do not feel that I can mention one without neglecting a very long list of the others, and therefore, gentlemen, all that I can say is that I thank you very much indeed.

C. A. Adams (communicated after adjournment): Not having been present during Mr. le Maistre's address, I am taking this opportunity of expressing myself on two phases of this subject which are close to my heart.

The first of these has to do with the very broad, one might almost say philosophic, aspect of standardization.

The world is today in the throes of its greatest war. But there are other types of conflict between nations or more often between the various groups within nations, which are always with us, and whose possibilities in the way of producing real human unhappiness and misery are quite as great in the long run as those of a war even of the magnitude of that now in progress.

The more one studies such conflicts the more one becomes convinced that one of the most important causes is the lack of mutual understanding and appreciation as between the various groups involved. This lack of understanding is in turn due to the various barriers which separate the groups, and one of the greatest of these barriers is the lack of a common and accurately understood language, this last word being employed in its broadest possible sense. For example, contemplate the large number of disputes based upon different interpretations of the same document, even when the document has been drawn by experts with the greatest care, and with the special aim of avoiding vagueness. How much more difficult it is to avoid misunderstanding between two groups having widely differing life experiences, customs and standards, or again between peoples of different traditions and speaking different tongues.

One of the most important functions of any Standards Committee is to establish within its own field just such a precise and compact language which will be acceptable to all concerned, *e.g.* it is obviously of the utmost importance that we all understand the same thing, when we say that an alternator has a continuous rating of 1000 kv-a. Yet it took your Standards Committee many years to produce a satisfactory and generally acceptable definition of "Rating", and a considerable part of our present rules is devoted to the defining and elucidating of this one word and to explaining how the rating of a machine can be checked by test.

The process by which this result was obtained is in a large degree typical of all the work in this field, and at the same time illustrative of the chief point of these remarks.

First the various groups involved were brought together; they exchanged data, experiences, theories and points of view; until apparent conflicts of interests disappeared through a process (sometimes stormy) of mutual education. In other words they finally came to an understanding through the evolution of a

common language. That this language is still imperfect is obvious, but it serves a very useful purpose even now, and will doubtless grow in usefulness as it slowly evolves.

Taking the next step, into the international realm of engineering standardization, we find the same process at work; and although a little more slowly, yet to the same end; a gradual evolution of an international understanding, a substantially universal language, and a cordial spirit of co-operation, which if it extended only to the confines of the particular realm of human endeavor here under discussion, would nevertheless be an important factor in the hastening of that time when the term "human brotherhood" will apply beyond the borders of each particular little group.

To be sure this international movement appears to be temporarily arrested in certain quarters, but I for one, am confident that the engineers of the waring nations will be among the first to set aside partisan feelings for a broader common sense spirit of co-operation.

This brings me to my second point, which is the personal one. In all of this work where representatives of the various groups get together, the personal element is a most vitally important one. One needs the courage of his convictions, but the narrow minded partisan must in the long run give way to the broader co-operative spirit. Many of the chasms of unfriendly misunderstanding which develop in all fields of endeavor might easily be bridged if there were more of this spirit abroad.

In this connection I cannot refrain from adding my tribute to Mr. le Maistre. He came to us as delegate of the Engineering Standards Committee of Great Britain; he sat with us in informal conference or in formal meeting day and night in several periods aggregating two solid weeks; he presented the suggestions of the British Committee in the broadest possible spirit, but did not confine his discussions to that part of the subject; he entered into the spirit of our meetings and became one of us, giving us generously of his time and experience; his personal assistance was of such an order that we shall hereafter feel any revision of our rules incomplete without his suggestions.

This is the kind of getting together, of co-operation, of learning each others' language, of building up a friendly understanding as contrasted with an unfriendly suspicion, which was referred to in the first part of these remarks. It is work of this kind which breaks down the barrier of misunderstanding, and draws groups and nations closer together.

The engineering profession, not only in Great Britain but the world over, is thus to be congratulated in the recent appointment of Mr. le Maistre as General Secretary of the Engineering Standards Committee of Great Britain, and the electrical engineering profession is to be specially congratulated in still retaining his services as General Secretary of the International Electrotechnical Commission.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

ELECTRIC DRIVE FOR REVERSING ROLLING MILLS

BY WILFRED SYKES AND DAVID HALL

ABSTRACT OF PAPER

The manner in which the electrically driven reversing rolling mill has been adopted especially within the last year, is surprising in view of the strongly entrenched position of the steam driven mill. Electric motors have been used for many years on mills running continuously in one direction, but many motor users have felt that the reversing mill could be better handled with the steam engine. There are naturally many characteristics little understood, due to the limited use in this country today.

This paper answers some of the questions which are raised and describes the constructions that have been found desirable.

THE ELECTRICALLY driven reversing mill has been the subject of a number of papers* before the Institute in which the general scheme of operation has been described in detail. Since these papers were presented this type of mill has been considerably developed and a number of installations made. In addition, a great many new mills are being equipped, and within the next year there will be 15 reversing mills in operation in the United States. The great success that has been attained appears to warrant a review of this subject together with a discussion of some of the characteristics of this equipment.

Since the first installations were made and mill engineers have been in a position to personally check the operation and economy of equipment, the steam engine for reversing mills has been comparatively neglected. As an indication of the position that the electrically driven mill has attained, the engineers of one of the large steel companies upon making investigation regarding the type of drive to install for new reversing mills, stated that the electric drive would undoubtedly in the very near future entirely supplant the reversing steam engine except

*Electrically Driven Reversing Mills, by Wilfred Sykes. A. I. E. E. TRANSACTIONS, 1911.

Operation of a Large Electrically Driven Reversing Mill. By Wilfred Sykes, A. I. E. E. TRANSACTIONS, 1912.

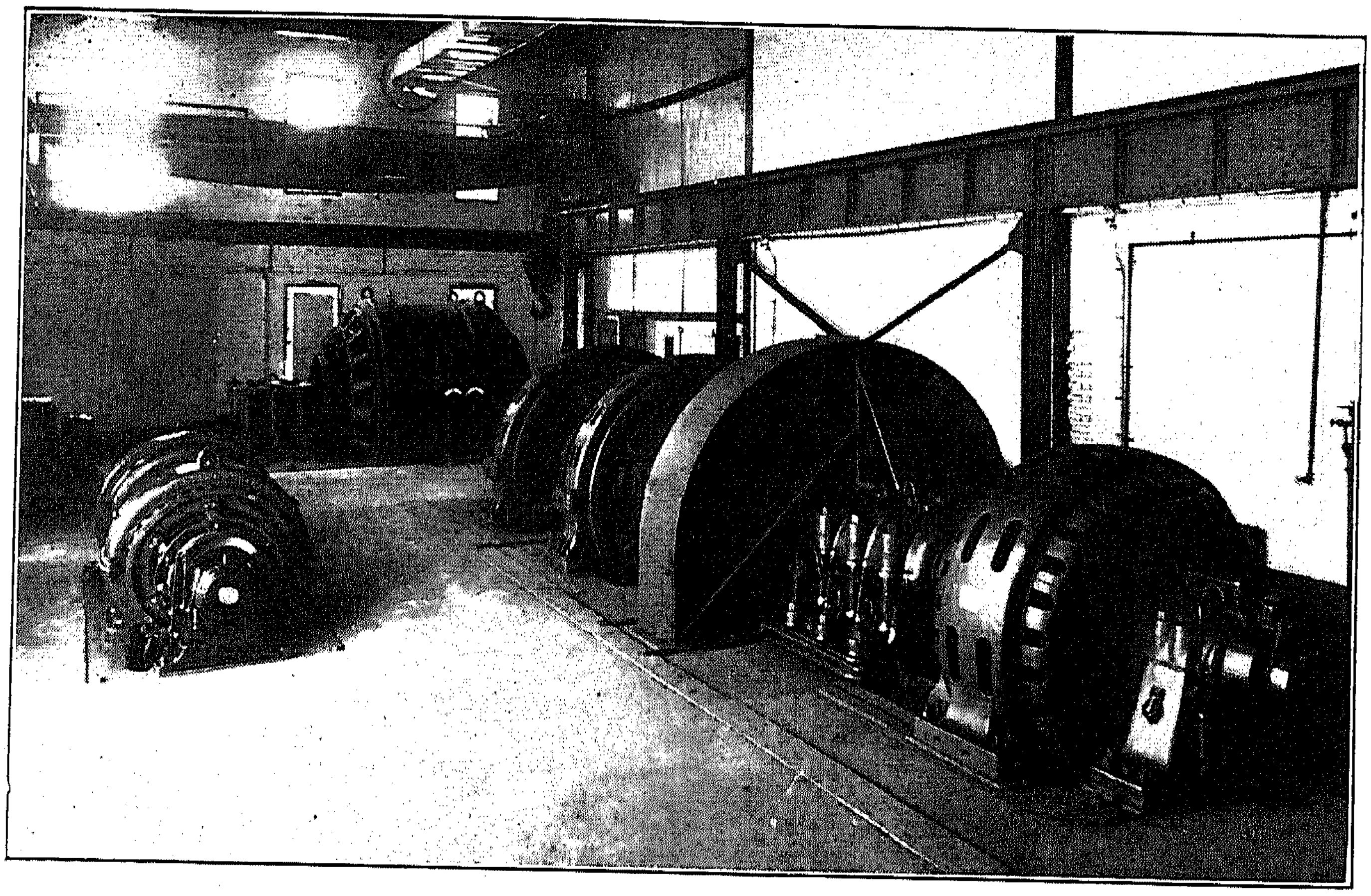
Electrification of a Reversing Rolling Mill of the Algoma Steel Co. By B. T. McCormick, A. I. E. E. TRANSACTIONS, 1912.

in perhaps certain peculiar cases. Practically all the new installations of reversing mills contemplated at present will be electrically driven. Although the electrically driven mill has not so far made the advance in this country that it has in Europe, it is characteristic of American practise to quickly adopt any device which has been demonstrated to suit the American conditions. The reversing mill as developed in this country and as shown by the existing successful installations, differs in many respects from European construction. Special attention has been given to the mechanical construction of the reversing motor and every care has been taken to insure that the machine will stand the much rougher handling which it receives in this country.

As pointed out in one of the papers previously read before the Institute, the reversing plate-mill drive installed at the South Chicago plant of the Illinios Steel Co. was the second drive of this type to be put into operation in the world and it was designed without knowledge of the fact that a similar arrangement was being constructed in Europe. It was a number of years later before a reversing blooming mill was electrified.

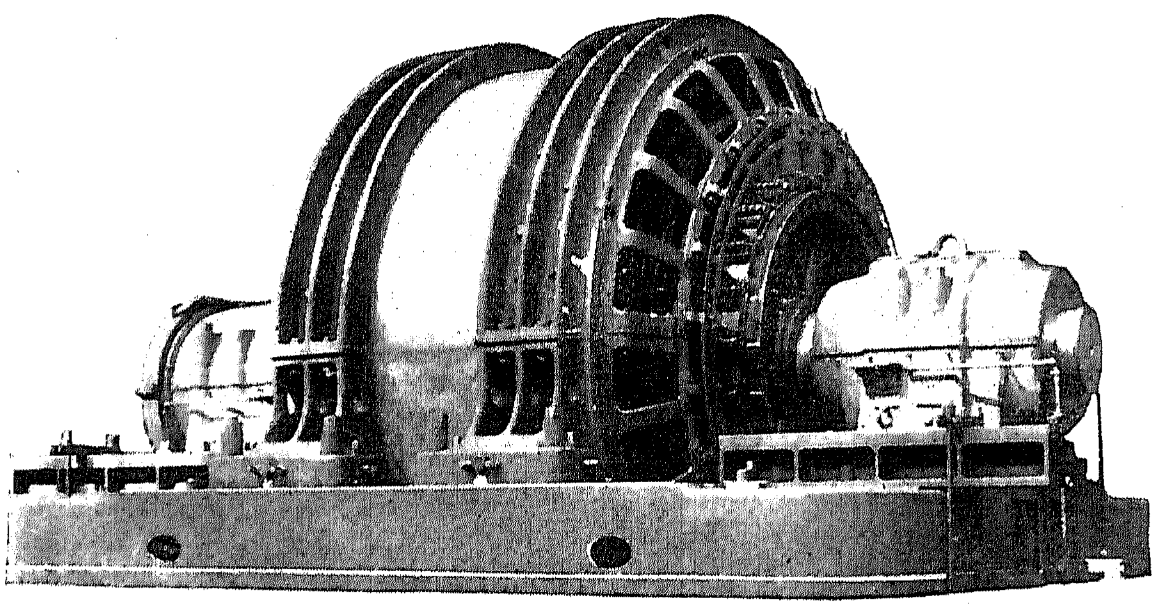
The first successful installation of a reversing blooming mill was that of the Steel Company of Canada at Hamilton, Ont. This installation consists of a double reversing motor capable of developing about 10,000 h.p. maximum, and is supplied with power from a flywheel motor-generator set with two generators. The complete electrical installation is shown in Fig. 1. This mill has been in operation for over three years with very satisfactory results. It is at present working at a rate very considerably in excess of the capacity specified when it was installed. The following are particulars of the mill and driving equipment.

Size of ingot	
Weight	15 by 17 in.
Finished material	4000 lb.
Elongation	4 by 4 in.
Number of passes	16
Capacity, tons per hour	19
Roll diameter	60
Pinion diameter	30 in.
Speed, full motor field	34 in.
Speed, weakened motor field	70 rev. per min.
Driven from motor	100 rev. per min.
Number of motors	direct
Voltage across each armature	2
Maximum operating torque	600
Maximum motor horse power	900,000 ft-lb.
Number of generators	10,000
Rated power of driving motor of set	2
Weight of flywheel	1800 h.p.
Speed of flywheel set	100,000 lb.
	500 rev. per min.



[SYKES]

FIG. 1—GENERAL VIEW OF FLYWHEEL MOTOR GENERATOR AND REVERSING MOTOR INSTALLED AT THE PLANT OF THE STEEL COMPANY OF CANADA.



[SYKES]

FIG. 2—REVERSING MOTOR BUILT FOR BETHLEHEM STEEL COMPANY ASSEMBLED IN SHOP.

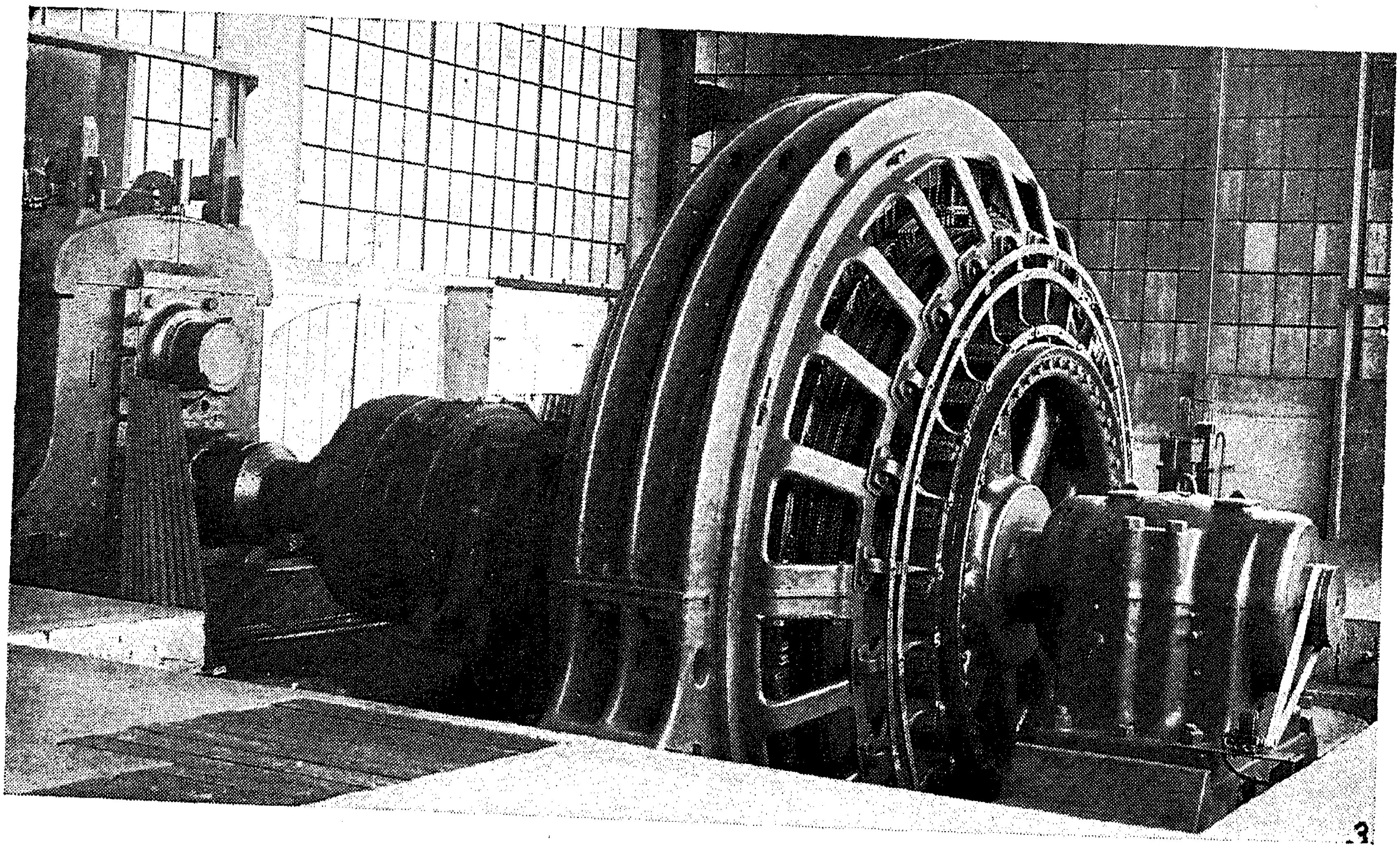


FIG. 4—REVERSING MOTOR DRIVING BLOOMING MILL OF CENTRAL STEEL COMPANY [SYKES]

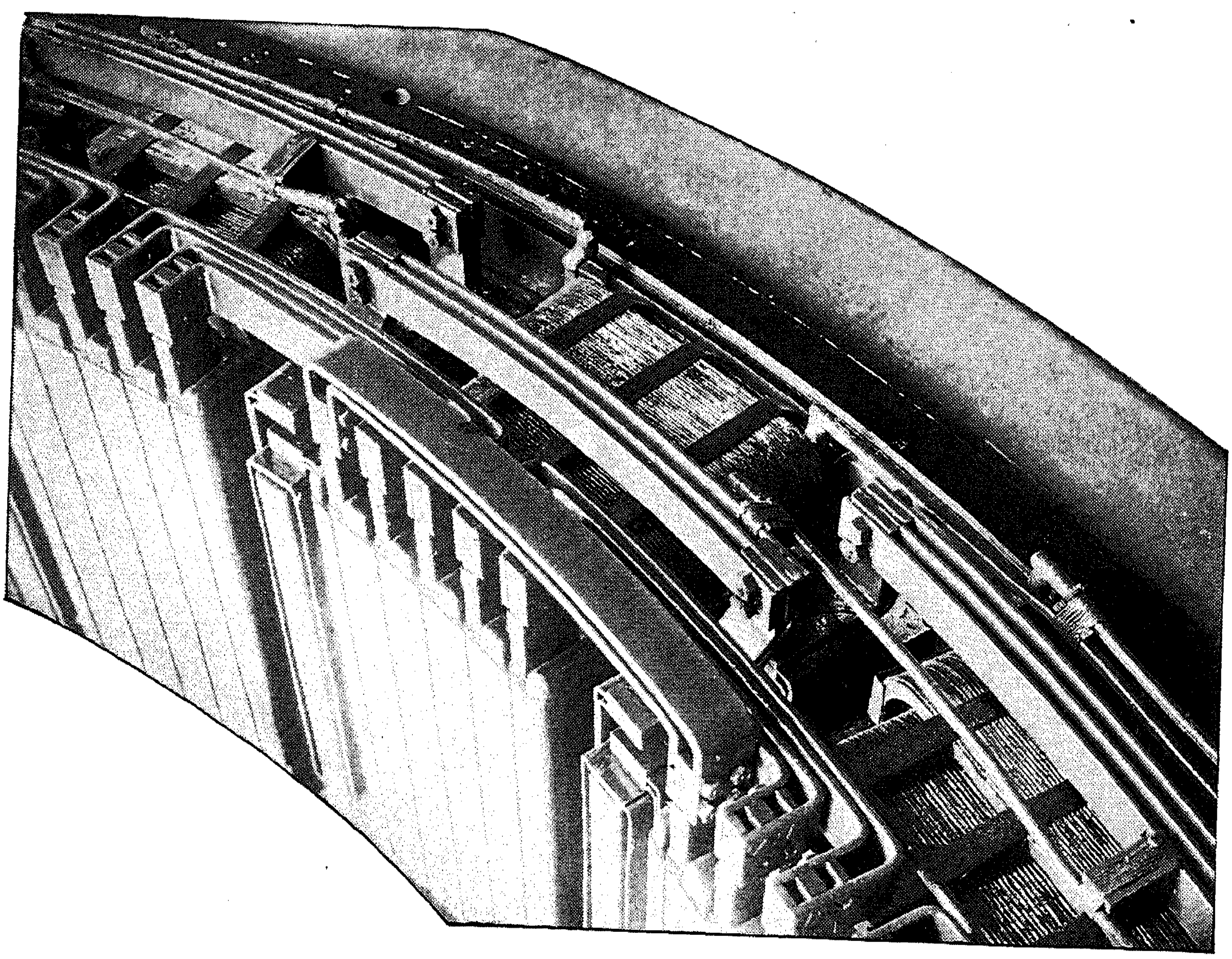


FIG. 12—COMPENSATING AND COMMUTATING POLE WINDINGS AS USED IN REVERSING MILL MOTORS [SYKES]

The largest installation at present in operation is that of the Bethlehem Steel Co. which drives the 35-in. blooming mill at the Lehigh Plant. Fig. 2 shows the motors as assembled in the shop before shipment. Both of the above mentioned installa-

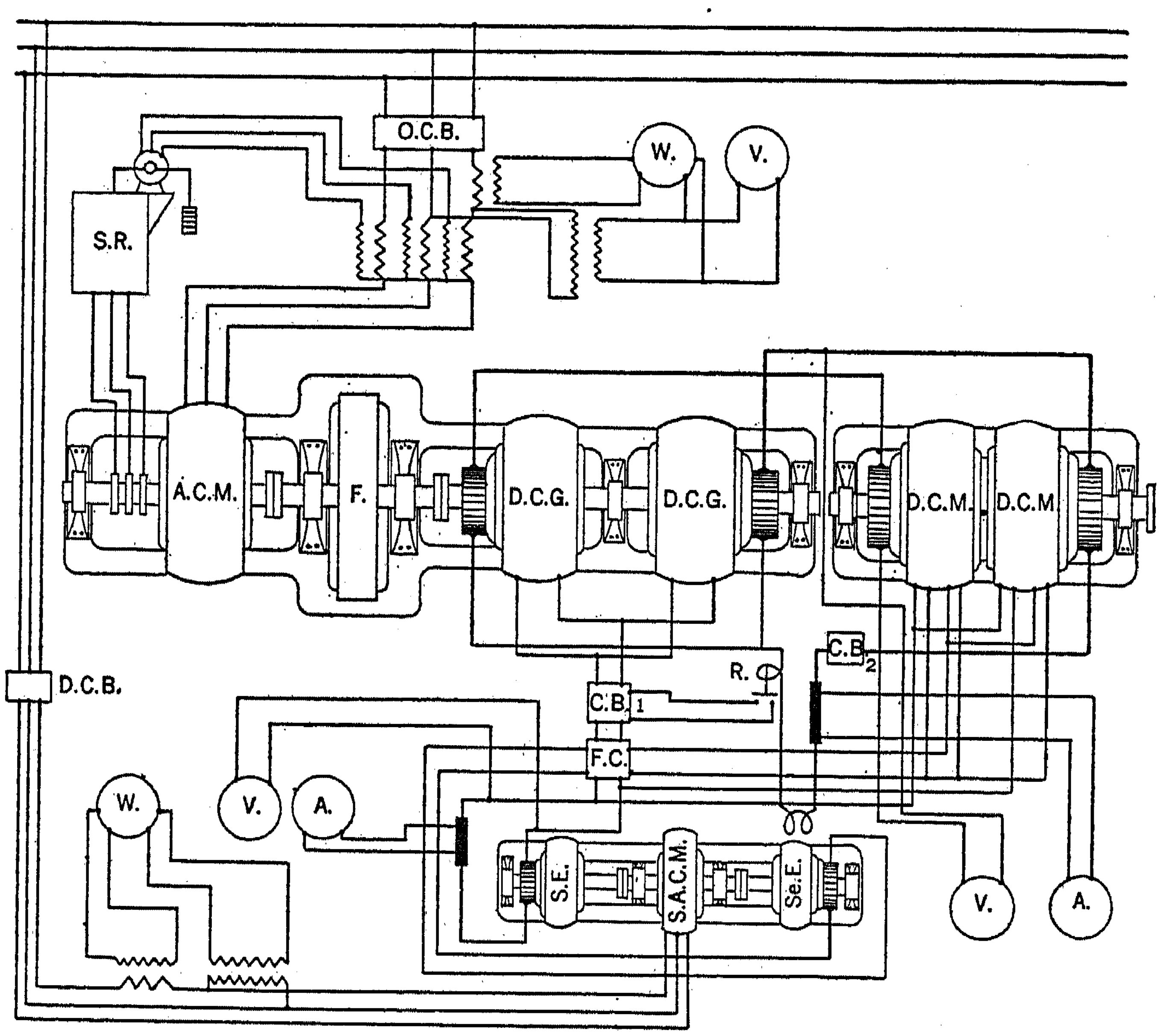


FIG. 3—SCHEMATIC DIAGRAM OF CONNECTIONS OF LARGE REVERSING MILL DRIVE

OCB —oil circuit breaker with no-voltage and overload trip
SR —automatic liquid slip regulator
ACM —alternating-current wound-rotor induction motor
DCG —direct-current separately-excited generators
DCM —direct-current separately-excited roll motors
CB —circuit breakers—1 generator field—2 main circuit
R —relay for operating circuit breaker in generator fields
FC —field controller
F —flywheel
SE —shunt exciter for generator and roll motor fields
SeE —roll motor exciter the field of which is separately excited by the main d-c. circuit
SACM —alternating-current squirrel-cage induction motor
V —voltmeter
A —ammeter
W —wattmeter

tions have double motors due to the amount of power required. The machines are arranged as shown by diagram, Fig. 3. A somewhat similar drive is installed at the plant of the Central Steel Co., Massillon, O., but a single motor is used for driving the mill, the capacity of the motor being approximately 8000 h.p

This motor is shown in Fig. 4, which illustrates the machine as installed for driving the mill. Characteristics of these mills are as follows:

	Bethlehem Steel Co.	Central Steel Co.
Size of ingot	19 by 23 in.	18 by 20 in.
Weight	10,000 lb.	5,000 lb.
Finished material	4 by 4 in. up	4 by 4 in. up
Elongation	10–12 av.	Up to 20
Number of passes	17–21	19–21
Capacity, tons per hour	100	60
Roll diameter	30 in.	30 in.
Pinion diameter	35 in.	34 in.
Speed, full motor field	40	50
Speed, weakened motor field	120	120
Driven from motor	direct	direct
Number of motors	2	1
Voltage across each armature	600	700
Maximum operating torque	1,550,000 ft-lb.	750,000 ft-lb.
Maximum motor horse power	12,000	8,000
Number of generators	2	1
Rated power of driving motor of set	2,000 kw.	1,500 kw.
Weight of flywheel	100,000 lb.	60,000 lb.
Speed of flywheel set	375 rev. per min.	375 rev. per min.

In the recent installations the reversing motor is arranged to have the characteristics of a compound machine. This is obtained indirectly through a series exciter. The current to be handled in the main circuit may be as high as 10,000 amperes, and it is obvious that it would be extremely difficult to reverse the series field each time the motor is reversed, which would be necessary to keep both fields in the same direction. A series exciter is therefore used, the voltage of which is proportional to the current flowing in the main circuit. The armature circuit of the series machine supplies a separate winding of the field of the motor which may be readily reversed when the direction of rotation current is changed. The switches for reversing this field are operated from the same point on the master switch that reverses the field of the generator. The use of a motor with compound characteristics makes the operation of the mill a good deal easier on the mechanical equipment as the drive has more or less "give" to it. At the same time if there is an extreme load due to excessive draft or cold steel, the motor characteristics tend to compensate by automatically increasing the torque available and decreasing the speed.

Although the electrically-driven reversing mill has been practically adopted universally for all new installations there is still some misapprehension as to its operating characteristics.

It is of course natural that engine builders will fight the development of the electric reversing mill drive as much as possible and the following advantages have been claimed by one of the prominent engine builders:

1 *First Cost.* The first cost of the reversing engine is only a small fraction of the aggregate cost of an electric drive (steam turbines, generators, converter sets, motors, field controls and auxiliaries).

2. *Cost of Operation.* The modern reversing engine uses no more steam to do the work required than an electrical drive.

3. *Energy Saved During Reversal.* In a properly designed engine and mill *all* of the energy required for acceleration early in the pass is utilized at the end of the pass; while with an electric drive, due to the heavy rotating masses, only part is saved.

4. *Low Power Consumption with Partial Load.* High economy is obtained at partial load because a properly designed engine works with cut off. Low pressure control valves prevent all racing and speeding.

5. *Greatest Economy of Time.* A modern reversing engine accelerates in less time than will ever be possible with a motor on account of the smallness of the rotating masses of the reversing engine."

As these are points that can be directly answered from data already available on electrically driven reversing mills in the United States, the points are taken up in the order given.

1. The first cost of an installation does not consist only of the cost of the engine or of the motor driving the mill. In the case of steam drive there are a great many items to be considered which include boiler plant, coal and ash handling facilities, coal storage yards, steam piping, condensing system, water supply for the condensing system, and foundations. In the case of electric drive in addition to the reversing motor there is the flywheel motor-generator set to supply power to it and the generating equipment consisting of power house with its complete equipment, or if power is purchased the only items to be considered are the motor-generator set, reversing motor and the small amount of control apparatus. Many of the items entering into the cost of the drive depend upon the particular layout of the plant. For, instance the whole plant layout might have to be modified so as to enable boilers to be located within a reasonable distance of the steam consuming engines, and this

very often seriously restricts the arrangement of the mills and other units. It may cost a very considerable amount of money to supply water to the engine condensers, which must be used if reasonable economy is desired, whereas in the case of generating station it would naturally be located close to the water supply. This would also be the natural location if blast furnaces are installed, as in this case the boilers would be close to the blast furnaces and the blast furnaces will of course be close to the dock on which the ore is unloaded, if water transportation is used. In any case the blast furnaces would be located close to the water supply which is also desirable for the boilers. It is of course immaterial from the distribution standpoint where the generating equipment is located. This is not so with the steam driven plant due to the length of piping and the consequent losses. The statement that the first cost the reversing engine is only a small fraction of the aggregate cost of an electric drive is certainly not correct as will be shown by the following figures. These figures are based on the actual installation cost and while some of the items would undoubtedly have to be modified to suit different locations, these figures give some idea of relative costs of the equipments.

Cost of Equipment for Driving 40-in. Blooming Mill to Roll 60,000 Tons of Steel per Month, 24 by 24 to 8 by 8 in.

Electric drive with purchased power.	
Complete cost of reversing motor, flywheel motor generator set, exciters and control equipment....	$185,000
Foundations, wiring, etc........................	10,000
Total..........................	$195,000
Electric drive with power generated at plant.	
Complete cost of reversing motor, flywheel motor generator set, exciters, and control equipment....	$185,000
Foundations, wiring, etc........................	10,000
Proportion of power house cost, 2500 kw. at $50 per kw..........................	125,000
Transmission and outside wiring................	5,000
Total..........................	$325,000
Steam Drive.	
Compound reversing engine......................	$125,000
Condenser, exhaust piping, including pumps.......	25,000
Foundations....................................	10,000
Boilers, 2500 h.p., including stokers, coal and ash handling plant at $30 per h.p..................	75,000
Steam piping with covering, valves, etc..........	15,000
Water tunnel for condenser with discharge 8500 gallons of water per minute..................	50,000
	$300,000

2. The statement that the modern reversing engine uses no more steam than the electric drive indicates the lack of knowledge of what the electric drive requires. So that there can be no misunderstanding on this point, in Tables I and II are produced the figures from a paper read before the Engineers Society of Western Penna. by Mr. Karl Nibecker giving the results of tests on a reversing engine. This engine is one of the most modern installed in the United States and comparison between it and the electrically driven mill can be justly made. It will be noted

TABLE I.—STEAM CONSUMPTION OF REVERSING STEAM DRIVEN BLOOMING MILL

POUNDS OF STEAM PER TON

No.	Size		Elongations	Lb. steam per ton	Remarks
	Ingot	Bloom			
A	20 by 22 in.	7 by 6 in.	9.04	587	Cold ingot
B	20 " 22 in.	7 " 6 in.	9.04	490	Hot ingot
C	20 " 22 in.	7 " 6 in.	9.04	497	Good rolling
D	20 " 22 in.	7 " 6 in.	9.04	520	New engineer
E	20 " 22 in.	7 " 6 in.	9.04	518	New engineer
F	20 " 22 in.	7 " 6 in.	9.04	575	Bad rolling
G	20 " 22 in.	7¾ " 3¼ in.	15.1	767	New engineer.
H	20 " 22 in.	7¾ " 3¼ in.	15.1	610	Good manipulation
I	20 " 22 in.	11¾ " 3 in.	10.75	694	New engineer
J	20 " 22 in.	11¾ " 3 in.	10.75	625	Good manipulation
K	18 " 32 in.	23¾ " 4½ in.	5.13	522	Good rolling-cold
L	18 " 32 in.	23¾ " 4½ in.	5.13	423	Good rolling-hot
M	19 " 46 in.	36½ " 4¾ in.	4.63	356	Bad rolling
N	19 " 46 in.	36½ " 4¾ in.	4.63	292	Good rolling

TABLE II.—STEAM CONSUMPTION OF REVERSING STEAM DRIVEN BLOOMING MILL

Size		Number of elongations	Lb. steam per ton	Lb. steam per ton at	
Ingot	Bloom			5-Elong.	9-Elong.
20 by 22 in.	11¾ by 3 in.	11.5	643	444	591
20 " 22 in.	7¾ " 3¼ in.	15.0	600	375	505
20 " 22 in.	7 " 6 in.	9.0	495	350	495
18 " 32 in.	23¾ " 4½ in.	5.0	420	420	....
16 " 32 in.	29 " 5 in.	3.25	280	...	....
19 " 46 in.	36½ " 4¾ in.	4.75	300	...	....
18 " 32 in.	23½ " 3 in.	7.5	410	256	....

that these are tests of single ingots, but Table I shows the results of a series of six ingots rolled from the same size bloom from which a fair average can be obtained. Table III gives the results of tests made upon electrically driven reversing mills which are shown graphically in Fig. 5. These figures are not the results

TABLE III.
ELECTRICALLY DRIVEN REVERSING MILL.

Ingot	Bloom	Elongation	h.p-hr. per ton.	Remarks
18 in. round	$7\frac{3}{4}$ by $7\frac{3}{4}$ in.	4.66	11.4	High carbon
18 by 20 in.	3 " 8 in.	12.2	23	" "
18 " 20 in.	2 " 16 in.	9.2	19.4	Soft steel
18 " 20 in.	4 " 4 in.	18.5	26	
17 " 15 in.	4 " 4 in.	16.	24	
20 " 20 in.	5 " 5 in.	16.	25.5	
20 " 20 in.	8 " 8 in.	6.25	17.	

of tests of individual ingots but are based upon the power consumption of a large number of ingots rolled during the regular operation of the mill and they do not in any way represent figures made under ideal test conditions. They have been obtained by reading the watt-hour meter in the line supplying power to the reversing mill equipment including all losses and

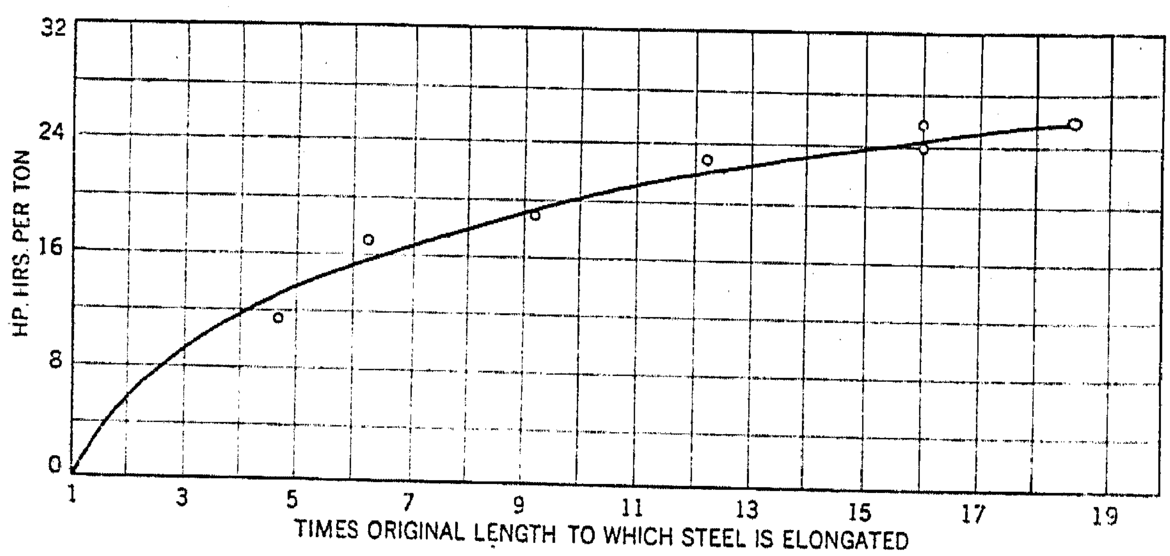


Fig. 5—Curve Showing Relations between Input to Electric Driven Reversing Mill and Elongation of Steel Rolled

represent the total power required to drive the mill. Fig. 6 shows the steam consumption of a 5000-kw. turbine, which is a common size in steel mills, operating under the same steam conditions as the steam-driven reversing mill. These steam conditions are not altogether ideal for a turbine as a higher pressure and superheat might be used, in which case still lower

steam consumption and better thermal efficiencies would be obtained. This curve of steam consumption includes the power necessary to operate the condenser circulating water pump and the air pump. Under normal operating conditions the turbine would run at 70 per cent of load and taking the steam consumption at this point, we find that one h.p-hr. can be generated for 13.6 lb. of steam. From the power requirement the total steam consumption can be calculated and it will be seen that this does not amount to more than from 50 per cent to 60 per cent of the best engines installed in the United States to date.

3. The question of saving accelerating energy is one that is given a good deal of thought by the engine builders as there is no way of storing it in the engine. The characteristics of the motor and engine are entirely different. It is true that if a mill is operated in an ideal manner the metal will leave the rolls at practically zero speed so that all the energy stored in the rotating

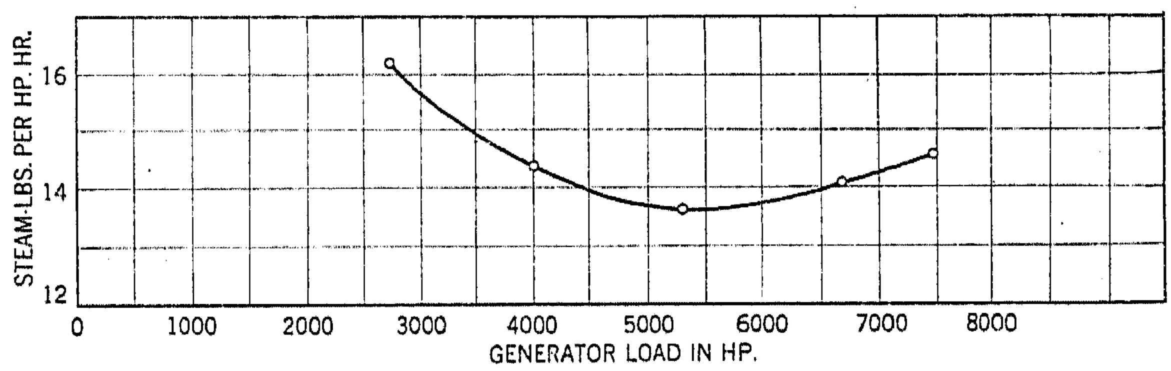


FIG. 6—STEAM CONSUMPTION OF 5000-KW. TURBINE, 150 LBS. STEAM PRESSURE, 28-IN. VACUUM

parts will have been returned to the mill and usefully consumed. Mills, however, are not operated in this way and neither the electric drive or the engine drive is operated in an ideal manner. Mills are handled by workmen and not by designers, and production is the object arrived at. The workmen are not interested nor do I believe it is possible to interest them, in the best conditions for obtaining low power consumption. This is a condition that must be reckoned with, and if possible the design of the equipment should be such that the power consumption cannot be affected materially by unskillful operation.

Due to the fact that the speed of the reversing motor is proportional to the throw of the controller handle and does not vary appreciably with the load, ideal conditions can be more nearly approached than with a steam engine. In the case of steam drive, it is quite common for the engine to race after the metal has left the rolls, especially if the draft has been a

heavy one, when there may be a large volume of steam in the cylinders which is not expanded, and which accelerates the engine parts. The engine must then be stopped and energy is required to do it. Fig. 7 shows the speed curve of a reversing engine taken from a recent test. It will be seen that in quite a number of cases the engine has raced after the metal leaves the rolls. For comparison a similar speed curve is reproduced of an electrically driven mill taken from the motor at the plant

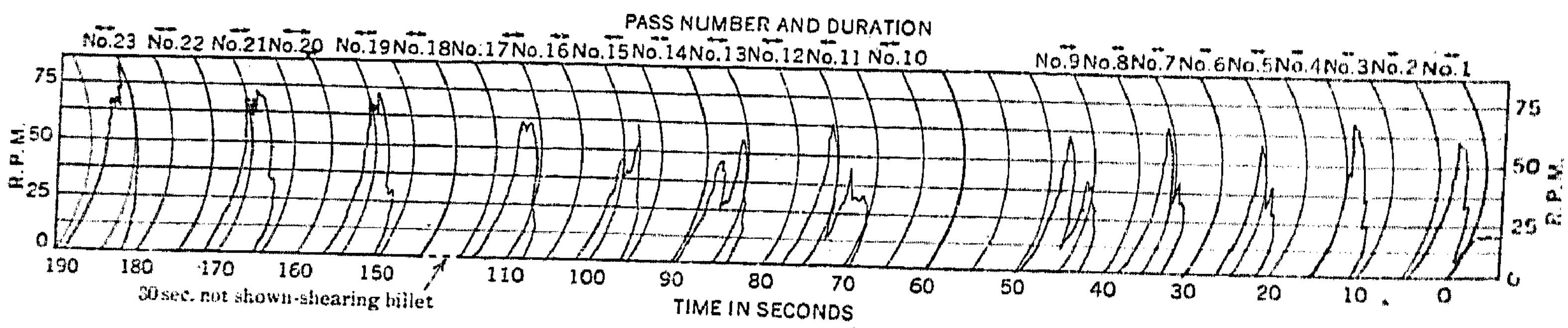


Fig. 7—Speed Curve of Reversing Engine. (*Note:* Only Alternate Passes shown to Obtain Large Deflection on Recording Instrument.)

of the Central Steel Co. In the case of electric drive, the motor is stopped by reversing its function and making it act as a generator. This is a natural characteristic of the equipment and enables the braking to be done very rapidly and also economically, as the energy stored in the rotating parts is returned to the flywheel of the set. The losses are only those due to the resistance of the windings. Whatever energy might therefore be lost due to the fact that the mill is not operated in an ideal

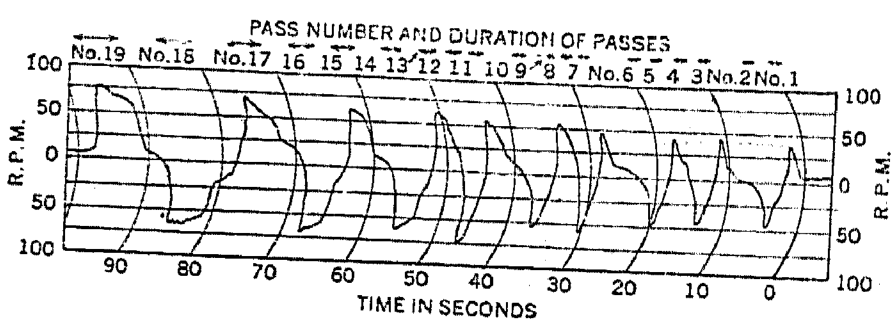


Fig. 8—Speed Curve of Reversing Motor Driving Mill

manner is returned to the flywheel and is available for the next pass. The whole point, however, is of little importance as it shows up in the relative power consumption of the two methods of drive which after all is the only criterion as to which is the better system to use.

4. With electrically driven mill the economy of course falls off somewhat as the output is reduced due to the continuous windage and friction losses of the flywheel motor-generator

set which are independent of the load on the machine. Outside of these losses it makes practically no difference whether one or 30 ingots are rolled per hour as far as the unit power consumption is concerned. In other words, the net power, (leaving out the constant losses) per ton of steel is practically independent of the quantity rolled. A somewhat similar condition exists with the steam engine inasmuch as it has certain constant losses due to leakage, piping and auxiliary power. However, outside of these losses the steam consumption will not be constant per unit of work done as the expansion conditions vary.

TABLE IV.
TIME STUDY OF REVERSING ENGINE

Pass No.	Time of entering pass-sec.	Manipulation
1	0.	
2	3.5	
3	9.7	Turn
4	13.	
5	17.2	
6	20.8	
7	27.2	Turn
8	31.8	
9	37.0	Turn
10	42.0	
11	50.0	Turn
12	55.0	
13	62.0	Turn
14	67.7	
15	75.8	Turn
Leaving press	79.3	

5. The question of the time required for operation is liable to be clouded very much by conditions that have nothing whatever to do with the time required for rolling the metal. It is undoubtedly true that the steam engine can reach certain given speeds quicker than the reversing motor. At the same time it does not necessarily follow that the reversing engine will roll any greater amount of metal than the reversing motor. It depends upon many other conditions such as the way the metal is handled on the tables, the maximum speed reached, and also time lost in the manipulation of the driving unit. Table IV shows the results of a time study brought out in a discussion

of the paper already referred to. Table V shows the results of similar figures taken from the reversing motor on the Central Steel Co. plant at Massillon, O. It will be seen that the time of entering the 15th pass in the case of the steam-driven mill was 75.8 seconds from the beginning of rolling and in the case of the motor driven mill 59.8 seconds. While it is not claimed that these figures show the advantages of one over the other system of drive yet they are sufficient to indicate that in practise the reversing motor will operate just as quick, if not quicker

TABLE V.
TIME STUDY OF REVERSING MOTOR

Pass No.	Duration of pass	Interval after pass	Time of entering pass integrated	Rev. per min. at entrance of ingot	Maximum rev. per min.	Rev. per min. as ingot leaves rolls
1	1.5	1.7	0	15.5	39	26.5
2	1.2	5.	3.2	36	47	31 *
3	1.7	1.6	9.4	12.5	47	28
4	1.4	1.5	12.7	23	48	27.5
5	1.7	1.4	15.6	7.8	44	20
6	1.7	5.5	18.8	23.5	55	31 *
7	2.0	1.2	26	11	50	18.5
8	2.0	0.6	29.2	23.5	62	12.5
9	2.5	1.4	31.8	15.5	56	31
10	2.2	3.7	35.7	23.5	59	31 *
11	2.5	0.8	41.4	18.5	55	14
12	2.6	1.2	44.7	23.5	78	31
13	2.9	2.0	48.5	23.5	62	34
14	2.6	3.8	53.4	28	67	51 *
15	2.8	2.0	59.8	7.8	64	31
16	3.0	4.2	64.6	15.5	76	55 *
17	5.0	4.2	71.8	23.5	74	31
18	5.0	5.0	81	23.5	70	62 *
19	6.5	2.5	91	22	80	12.5

* Piece manipulated.
Rolling 18 by 20 in. Ingot to 3 by 8 in. sheet bar blooms.

than the engine. Due to the ease of control, the motor drive is a good deal lighter on the operator and consequently he is able to continue running the mill at a maximum capacity with less fatigue than in the case of a steam-driven mill.

The design of the reversing motors and the generators supplying them with power presents many problems not encountered with ordinary direct-current machines. As the success of this type of mill depends upon the machines meeting the severe operating conditions without injury or deterioration, a brief review of the principal characteristics may be of interest.

There is no other class of service which might be properly compared with the requirements of a large reversing mill. The heavy torques, the sudden peak loads, and the quick reversals all call for apparatus of substantial mechanical design, and flexibility in electrical characteristics. The exchange of energy between the driving motor and the generator undergoes changes at a very rapid rate. In fact, the driving motor must perform the functions of a generator as well as that of a motor, and the supply generator may at one instant be furnishing current to the driving motor, and at the next instant it may be receiving electrical energy from the driving motor, and delivering mechanical energy to the flywheel. For example, the equipment at Bethlehem, which consists of two 600-volt motor armatures supplied by two 600-volt generator armatures all connected in series, may at one instant show a swing of 10,000 amperes, and at the next instant the swing may be of an equal value in the opposite direction. There must be rapid adjustments of flux conditions in both motors and generators in order to meet these reversals without showing harmful sparking at the brushes, and as the swings which occur many times a minute represent over-loads of 200 to 300 per cent, the design of the direct-current machines must be suited to these overloads, both in current carrying capacity and in flux conditions. Especially must the machines be designed for good commutation. This cannot be obtained at such overloads without making liberal allowances for the commutating flux, as the ratio which the commutating flux bears to the load must not be disturbed by leakage conditions, even at the overloads. This feature is more readily obtained by compensating the armature reactance to which further reference will be made, and this type of construction is of greatest importance, to successful results.

The choice of voltage per commutator and the use of two armatures, the commutators of which are connected in series for large powers, is deserving of a careful analysis, and this voltage should be selected with due consideration of the motor, the generator and the auxiliary apparatus. The following arguments are to show that, other things equal, it is desirable to adopt a relatively high voltage; viz. 600 volts and by series connection, alternating a motor with generator, derive all the benefits of 1200 volts.

The electrical equipment of a reversing rolling mill includes both the d-c. generator as well as the d-c. motor, and the gen-

erator does not furnish power to any other apparatus except the roll mill motor. The *voltage* should be of such a value as will give the best balanced equipments and the choice of voltage becomes a very important factor as the design of the entire equipment may be said to depend in a great measure upon the voltage selected.

The use of 250 volts has been common practise in rolling mills and it is natural that this voltage should be considered. However, for large capacities, there are many objections to so low a voltage, among which may be mentioned heavy currents, large commutators, larger machines, lower efficiencies, increased cost of auxiliary apparatus, higher maintenance charges and increased mechanical difficulties.

The magnitude of the current becomes a factor when the power required on peak loads may reach 15,000 to 20,000 h.p., and not only are the connections, cables and switching apparatus expensive, but the losses in these parts are roughly proportional to the currents. The approximate cost of these parts will vary inversely as the voltage.

The size of commutators and the number of brushes will be a direct function of the current and it is desirable to keep down the size of the commutators from at least three points of view —mechanical difficulties of construction, over-all length and cost. No part of a direct-current machine is so difficult to construct as is the commutator, and for this reason the construction of commutators has received, and will continue to receive the most careful consideration from both the design and the manufacturing points of view. So all important is the commutator and the commutation that when these are right, there is seldom any cause for complaint. Increased voltage not only reduces commutator length, but insures less overall length—an extremely desirable factor.

The efficiency of the equipment as a whole will be higher with increase of voltage within certain limits, as in such installations the peak loads are relatively high as compared with the average or mean load.

The commutating condition of the generator is one of the items which must be carefully considered in the selection of voltage, especially as economies can be effected by operating the flywheel set at a reasonably high speed. It is desired to consider whether a generator can be designed better for one voltage than for another, and what is a safe operating speed for

a generator of a given output and voltage. With a view of setting forth the relations of kilowatt capacity and speeds, the writer has chosen familiar voltages of 125, 250, 600, 1200 and 2500 volts, and has plotted a curve for each one of these voltages. These curves are shown in Fig. 9. There are certain fairly well established relations and limits in direct-current machines, which lead to limits of output. However, it is not so much these limits that we would direct attention to at the present moment, but the relation of possible outputs of different voltages. It will be observed that at 600 volts the possible outputs are greater than at either 250 volts or 1200 volts. This means that with the same degree of safety it is possible to make a larger 600-volt generator than a 250-volt or 1200-volt generator, for a given

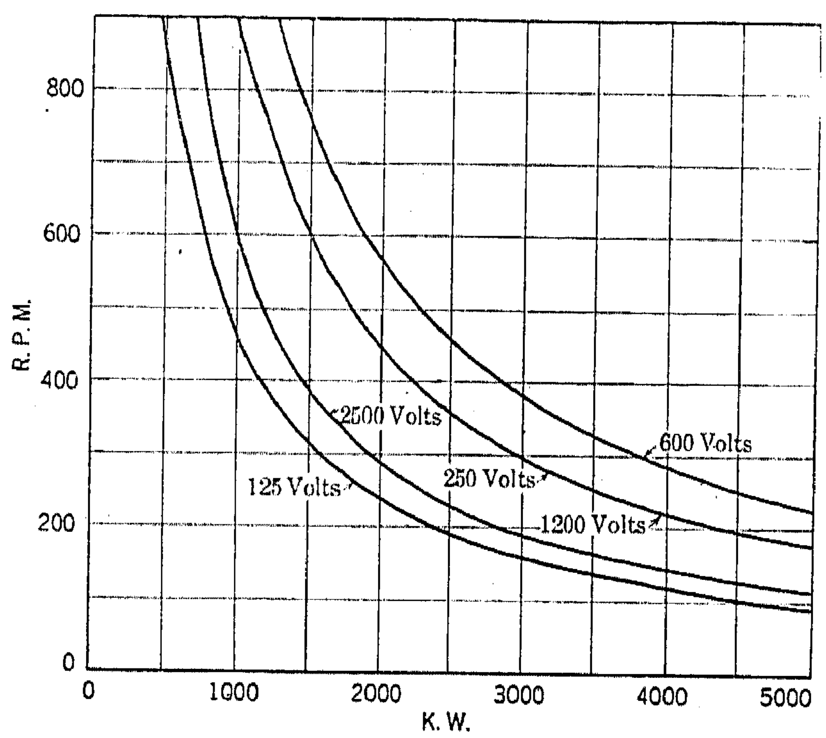


FIG. 9—CURVE SHOWING THE LIMITS WITHIN WHICH DIRECT-CURRENT GENERATORS CAN BE BUILT

speed. This relation applies at all speeds. It will be observed that the product of kilowatt output and rev. per min. is approximately a constant for a given voltage. This relation is frequently lost sight of in considering the possibilities of machines for large output, at high speed. The basis on which these curves have been made up depends upon setting certain limits. These limits are not definitely fixed quantities, as each designer will set limits depending upon the experience which he has had with various machines. The relation of these limits will in a measure determine which curve will be highest, and some of these limits are entirely independent of each other. The limits which determine the possibilities of high-voltage machines are entirely different from those which determine the possibilities in low-voltage machines. Curves could be drawn for all voltages in

a similar manner as these have been determined, but the more usual voltages are used for the sake of illustration, and they serve the purpose of showing the desirability of using a relatively high voltage for roll mill motors, such as we are considering.

As these curves represent limits it is of course understood that most machines will fall under them and the extent to which a machine falls within the curve will represent in a measure the ease with which that machine can be designed. We would emphasize the fact that the minimum cost for a given rating does not necessarily call for the highest possible speed, and the present day tendency of going to extreme speeds should be discouraged.

From these curves we deduce that 600 volts is a desirable selection per commutator for the generators and it is also evident that 1200 volts per commutator would be possible. A voltage

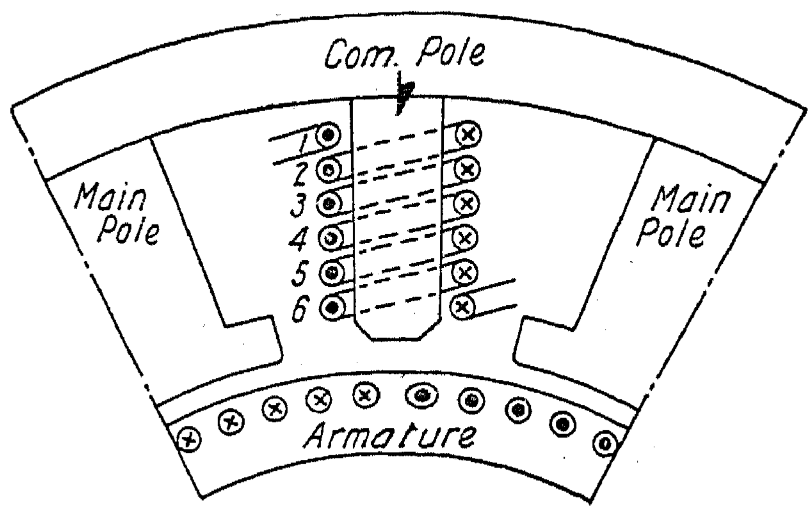


FIG. 10—COMMUTATING POLE WINDING

of 600 per commutator has proven well suited for the motor, as a lower voltage would lead to relatively large armature diameter. A very much higher voltage would require few poles with correspondingly heavy rotors, and either of the conditions is undesirable as low inertia effect is important.

TYPE OF WINDING

To obtain the best operation under heavy peak loads, which are subject to very rapid changes, for example, three times normal load, reversing at the rate of 30 times a minute, it is not only desirable, but it is necessary to neutralize to the fullest extent the distorting effects of the currents in the armature winding. The method of obtaining this result is to slot the pole face, and secure in these slots a bar winding which is connected in series with the armature, and making a number of conductors in the pole face just sufficient to neutralize the armature conductors

covered by the pole face. The excess winding necessary to produce a commutating flux is concentrated on the commutating poles, located midway between the main poles. The difference between the compensating winding and the interpole winding is illustrated in Figs. 10 and 11, which show the same number of conductors in both cases, but the conductors are shifted in position. In the plain commutating-pole machine, having all the commutating winding located on the commutating pole, the conductors are as shown in Fig. 10, whereas in the compensating pole machine, which has part of the compensating winding located in the main pole face and the balance located on the commutating pole, the conductors are as shown in Fig. 11. By locating in the pole face the ampere conductors which neutralize the armature reaction under the pole face, the distortion of the flux at the main pole face is prevented. This has a beneficial

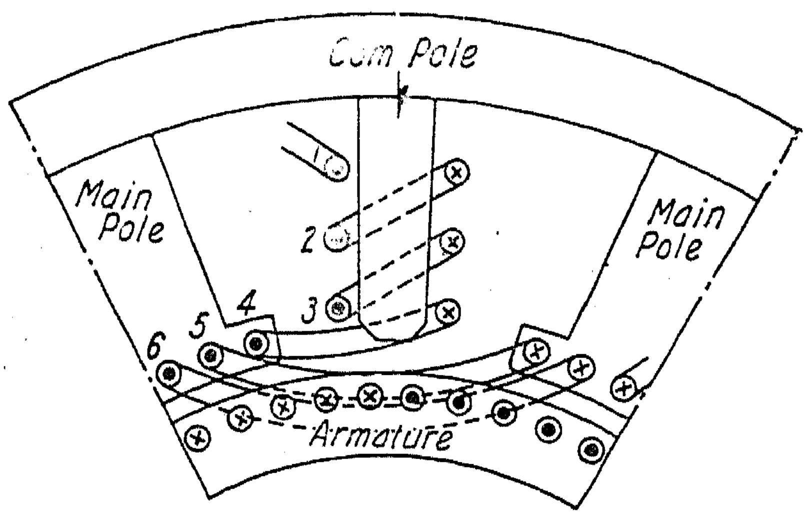


FIG. 11—COMMUTATING POLE AND COMPENSATING WINDING

effect in two ways. First, it prevents under sudden changes of load, a sweeping across the pole face of the main flux under the pole, and it prevents a distortion of the main flux which is a very important consideration, as this lowers the maximum voltage between adjacent commutator bars, which would otherwise obtain. As it is the maximum voltage between commutator bars, rather than the average voltage, which determines the design, the importance of this type of construction becomes evident for this class of service. Another very important consideration in this arrangement of the compensating winding is that the leakage from the commutating pole is very much less than would be the case if all of the windings were concentrated on the interpole. This fact permits the carrying of heavier overloads, and it is the overload capacity which determines to a great extent the suitability of machines for this class of service. It is evident that the leakage is very much reduced, when one

considers that the leakage is mainly between the main pole tip and the interpole, and that the magnetomotive force producing this leakage is made very much less by locating a large proportion of the ampere conductors in the main pole face.

This construction permits the operation of the machines through a wide range of voltage; in other words, the stability of the main flux is insured without regard to the strength of the main field winding. This is an important factor in the general scheme of control, as the speed of the motor and the direction of rotation of the motor depend upon the generator voltage and upon the field strength of the motor. These two factors must be susceptible to rapid changes and wide variations in order to effect the desired result.

In referring to the relative merits of commutating pole machines, versus machines with compensating winding, for this class of service, attention may be called to the fact that compensating windings are difficult of construction, in machines having very large current, as there is a limit to the desirable physical dimensions of a single pole face conductor. With heavy current machines, a suitable arrangement of compensating conductors is often quite a problem in a specific design. The most desirable arrangement is to have all compensating conductors connected in series, and the possibility of such an arrangement is limited by the capacity and voltage of the machine, and here again there is a decided advantage in not having the voltage too low, for large power capacities. For example, a single conductor having a cross section of more than two sq. in., is seldom used in the pole face winding. Assuming a current density of 1500 amperes, a single conductor, with all conductors in series, can be used on a 3000-ampere machine, which, at 600 volts, represents an 1800-kw. capacity. For larger current capacities, it is necessary to connect the conductors in parallel, and frequently the circuits are in parallel. In such cases, great care must be exercised in the building of the machines so as to have good joints, in order to insure the proper division of the current.

Generally speaking, the compensating winding of large capacity machines consists of a relatively small number of conductors, and simpler, better mechanical arrangements can be effected than are possible with smaller capacity machines. It is also desirable to design the compensating winding and the commutating pole winding so that no shunts will be necessary. This can readily be accomplished as it is possible to calculate very

closely the required ampere conductors, for compensating the armature reaction and furnishing the necessary excitation for the commutating pole. By avoiding shunts, one is insured of the simultaneous change of current in the compensating winding and the armature winding.

Field Windings

The type of field winding used on roll mill machines should be very simple, and such as not to be easily damaged. If a low voltage is used for excitation of the d-c. generator and d-c. motor field coils, these coils can be made of copper strap winding with a layer of asbestos between turns, and the bare edges exposed to the air. Such coils are almost indestructible by heat. Strap wound field coils arranged in two or more concentric sections insure a natural and easy ventilation.

Insulation

As this type of machinery is exposed to mill dust, and as this dust is likely to contain a large percentage of conducting material it is advisable in the design to embody more liberal creepage distances than are necessary for ordinary service. In order to combat, to a certain extent, the bad effects of dust, the armatures may be given a finish by rolling them in varnish and baking them. This produces an insulating film over all parts, and fills all the pores and small crevices in the insulation, and insures a slick finish which will shed the dust.

DISCUSSION ON "ELECTRIC DRIVE FOR REVERSING ROLLING MILLS" (WILFRED SYKES AND DAVID HALL), CLEVELAND, OHIO, JUNE 27, 1916.

K. A. Pauly: There are several points in connection with this paper by Messrs. Sykes and Hall to which I wish to refer in discussion. One of the first points which is worthy of attention is that of the rating given these motors: namely, a horse power corresponding to the maximum torque which they will carry without any mention of the time during which they will carry the load. All will agree that a rating on this basis is not only contrary to the recommendations of the A. I. E. E., but is very unsafe for the purchaser on which to base the relative capacities of competitive equipments for any class of service. That the idea of so rating these motors is a new one will become apparent to any one examining the publications of the company with which the authors are connected. The early publications showed, for example, 3000 h.p. as the capacity for the motors of the Steel Company of Canada now rated at 10,000 h.p. On this same basis, any one of the 6000-h.p. motors at the Gary Works of the Illinois Steel Company might be rated at 20,000 h.p.

As to the relative merits of the electrically driven reversing mill and its steam competitor, it is difficult to discuss a question of this magnitude in generalities, because there are so many factors affecting the problem, which are more or less important, depending upon the special conditions obtaining in individual cases. However, the characteristics of motors are in most of the essential details especially adapted to rolling mill conditions. They permit of the centralization of the steam plant and the generation of power in high speed, highly efficient units. The authors have made the mistake frequently found in comparing estimates of the relative operating costs of steam versus other methods of drive. Why stop with the steam consumption, when one of the greatest savings results from the increased boiler efficiency due to the more uniform demand for steam made possible by the use of the fly-wheel motor-generator set equalizing the load in the electrically-driven mill. Tests would indicate that boiler efficiencies may be raised twenty per cent or more by relieving the boiler of these excessive demands for steam required by reversing engines.

My experience indicates that a comparison on the proper basis including all the items of first cost, chargeable against each method of drive, would show little if anything in general in favor of steam equipment in first cost, and will always show the electrically driven mill to be lower in operating costs. The speed and torque characteristics of the motors are ideal, there are no tendencies toward excessive speeds when the piece leaves the rolls and the motor is always in a position to exert its maximum effort when the maximum power is required.

The figures and curves of power consumed in rolling given by

the authors, check within reasonable margin of the experience of the writer.

In considering the requirements of reversing rolling mill motors, it is interesting to note the similarity between the factors affecting their electrical design and those for a mine hoist. Both are required to accelerate rapidly, and to carry very heavy dead loads, during acceleration. In fact, in these respects the requirements of a mine hoist motor are frequently more severe than for the reversing mill motor. The roll motor is required to accelerate but little in addition to its own armature, and usually reversal and acceleration to partial speed are accomplished without any dead load, although the equipment should have sufficient capacity to accelerate rapidly with the piece in the rolls. On the other hand, the hoist motor must accelerate in addition to its armature the drums, ropes, cages and load which may be equivalent to several times the armature, and must always handle full load throughout the acceleration. It is true that the time allowed for accelerating a mine hoist motor is more than that allowed for the reversing mill motor, but the increased time is not proportional to the increased load to be accelerated, so that frequently from the standpoint of peak loads, the requirements for the mine hoist motor are more severe than those for the reversing mill motor.

The shocks to which a reversing mill motor is subjected are, of course, more severe, and very much more so than those to which a mine hoist motor is subjected, but are the same as those to which the ordinary non-reversing steel mill motor is called upon to meet, so that the reversing mill motor becomes essentially a direct-current motor capable of withstanding the peak loads met with in mine hoist service, constructed mechanically to withstand the shock and vibrations incident to rolling with the windings held firmly to prevent injury from the mechanical and electrical shocks.

The all important question is production, and in my experience the steam advocate has made a greater point of the speed of the steam mill as compared with the electric mill than he has on the questions of economy or first cost, although many have claimed these advantages also, and the present electrically driven mills are referred to by him as being slow due to the time required to accelerate. In this extremely important detail, the characteristics of the reversing rolling mill motor differ from those of the mine hoist motor apart from the effect of the time of reversal on the peak current taken by the motor. It is well known that time is required to build up and discharge a magnetic field: the rate being dependent upon the time-constant of the field winding.

The importance of this is suggested by the author, but apparently in the equipment thus far installed every reasonable means has not been resorted to, to bring about a rapid change of field and resulting rapid acceleration and retardation. The accumulative compound windings on the motors tend to increase the time of rolling by lowering the rate of acceleration and decreasing the

time of retardation. This compounding is not necessary to protect the mill any more than it is necessary to protect non-reversing mills driven by direct-current or alternating-current motors, many of which are driven by motors without this provision or its equivalent. The compounding, of course, relieves the motor and generator from electrical shocks sufficiently to permit the use of slightly smaller equipment, but this saving is made at the expense of output from the mill. In the equipments we are now building for this work, we will not only take advantage of the shorter time required for accelerating and retarding the shunt motor to reduce to a minimum the time required for rolling, but are using in addition a special system of control, which will be described later in a paper. This takes advantage of the actual characteristics of the rise and fall of the magnetic field to produce a maximum rate of acceleration and retardation of the roll motor, thereby obtaining a faster operating reversing mill than any thus far built.

One of the most important details in the construction of a reversing mill equipment is the motor shaft, and in many instances this detail has been rather slighted. It is true that these shafts are protected by breaking spindles, but it must be borne in mind that the breaking of a spindle must in no way endanger the shaft. A moment's consideration will convince anyone that the motor shaft should be at least one-third larger in diameter to even protect it against injury from a strain sufficiently great to break the breaking spindle; even then there will be little or no factor of safety in the shaft, in spite of the difference in material used for shafting and spindles. In addition to this, the shaft is frequently subjected to extremely severe bending moments in the event of the breaking of a spindle on the diagonal. It has been our practise to recommend shafts much stronger than those installed, and I cannot but feel that eventually serious delays are bound to result from unnecessary weaknesses in this feature.

The question of motor voltages is too elementary to warrant discussion, although considerable importance seems to have been attached to it by the authors. Practically all of the reversing mill motors installed, including the first one, have been designed for voltages ranging from 550 to 750 volts, and where more than one motor has been used, they have been connected in series, resulting in a voltage of the combination from 1000 to 1500 volts. Here as in most problems, involving larger powers, it is essential to use as high voltage as is consistent with reliable operation and reasonable first cost, and the writer feels safe in predicting higher voltages for this work when more experience has been gained with high-voltage direct-current units of large capacity.

The question of windings, compensated and commutating, is also ancient history, the equipments for this service always having been provided with these special means for improving commutation.

E. S. Jefferies: The question brought out in Sykes' and Hall's paper regarding engine builders' claims is very interesting, and

I would like to point out a few results obtained on the Steel Company of Canada's mill referred to in their paper.

This mill has been operating since the early part of 1913 with very good results, and the experience gained brings out some very interesting answers to the five general questions raised by the steam men in favor of steam rather than electric drive. In the tables herewith, are complete costs covering this installation, and operating costs for the three years 1913 to 1915, and an average for the same period.

As the Hamilton Mill purchases power, I cannot give any comment on the relative costs of steam and electrical drive. However, in Table I is given a comparison showing the operating costs, interest on investment, depreciation and miscellaneous charges covering this particular installation. This shows an average total cost for the three years of only 43.1 cents per ton. This figure includes a depreciation charge which considers the installation as valueless at the end of a 20-year period, and a miscellaneous charge which includes all power for lighting, tables, crane, conveyor, pumps, motors, etc., used in this mill. The largest item, power cost, is exact, as it is metered, and the other items are charges made direct with no estimating, the result being that the total is an exact cost without any estimation whatever, in arriving at the results. These are the actual book figures.

TABLE No. 1.

Year	1913	1914	1915	Average or total	Per cent
Operating	9 months	8 months	12 mo.		
Tonnage,	119,230	92,622	174,460	386,312	
Kw-hr. per ton,	23.9	22.8	21.5	23.4	
Power cost,	\$.0160	\$0.153	\$.0144	\$0.157	36.40
Repairs and maintenance	0.077	0.009	0.004	0.006	1.40
Miscellaneous supplies	0.004	0.005	0.003	0.004	0.90
Labor in operation	0.014	0.016	0.013	0.014	3.25
Total operating cost	0.185	0.183	0.164	0.181	
Interest on investment (\$156,000)	0.078	0.101	0.054	0.73	16.90
Depreciation (20 years)	0.065	0.084	0.045	0.060	13.95
Total operating and fixed costs	0.328	0.368	0.263	0.314	
Miscellaneous	0.126	0.133	0.115	0.117	27.20
Total cost	0.454	0.501	0.378	0.431	100.00

The question of energy saved during reversal is a very interesting subject in connection with a paper of this kind. How many rollers on reversing mills in this country are paid straight time? How many are paid tonnage rates? The answer is that practically every mill is paying tonnage rates, with the result that speed is the sole question in the operators' mind. Furthermore this speed is obtained by using live steam to reverse the engine rapidly. In a motor-driven mill a certain per cent of the stored

energy in the rotating parts is saved by regeneration, and is stored in the flywheel for future use, regardless of operating conditions. The one great advantage in answer to question 4 of low power consumption with partial load is that the motor-generator set can be disconnected from the line when the mill is idle, thereby entailing no stand-by losses, such as are met with in steam installation.

The time taken for the Hamilton motor to reverse is still ahead of the handling of the metal on the tables, manipulation, screw-down, etc. That is, the motor is waiting on the mill. Since the figures given by Sykes and Hall on this mill were taken, we have developed a new governing relay which has given us considerably more positive protection and allowed more speed and, therefore, capacity. We have obtained a speed of 125 rev. per min. on our long passes which when rolling from sixteen to seventeen elongations, saves considerable time.

The advantage of an electric mill may be summed up as follows:

1. Low cost of power.
2. Low cost for repairs and maintenance.
3. Small time to get under way from complete shut-down to rolling conditions.
4. Speed proportional to displacement of controller lever from off position.
5. Part of rotative energy of mill parts recoverable for useful work.
6. Stand-by losses nil.
7. Simplicity of control.
8. Few delays necessary.
9. Motor does not race when steel leaves rolls.
10. Constant turning moment.
11. Ideal load to add to any generating station.
12. Lends itself to centralization of power.
13. Simplified mill lay-out.
14. Mill breakages less.
15. Small area or ground space needed.

The floor space necessary for the equipment described was 40 feet by 125 feet, which allows ample room between machines and wall and switchboard, no apparatus being cramped in any way. A 40-inch mill could easily be installed in this same area. In case of necessity the flywheel set need not be located in close proximity to the mill motor, so that in adapting a mill under extreme conditions where very little floor space was available, the flywheel set could easily be located some distance away where more area could be obtained. The real estate charges on some mills located in thickly settled communities must be considered, and in comparing this area with the area necessary for boilers, coal handling machinery, steam engines, pumps, etc. the result is good.

After the mill has been down for any reason, the time necessary for the attendants to have the entire equipment ready for

maximum rolling conditions is less than ten minutes. It is doubtful whether a steam boiler equipment could be gotten under way from absolute standstill to running conditions in less than four hours. The simplicity of the control as compared to the levers, links and auxiliary cylinders necessary for the steam engine is very noticeable. The entire control wiring between pulpit and power house is contained in a one-inch conduit. All parts of the control are entirely accessible, and any part needing repairs can be changed in a very few minutes. Repairs have been exceptionally low, the largest item being the brush renewal. Delays in the last three years due to this equipment exclusive of the development period, have not amounted to twenty-four hours, and this period was taken up at various times more to be doubly sure that the equipment was in good order rather than take any chance.

When the mill is idle, the flywheel set can be disconnected from the line and allowed to rotate, which means that there is absolutely no loss as compared to steam equipment having to keep the boilers under steam, the steam-line condensation, small leaks, etc. When the steel leaves the roll, there is no racing, as would be the case in the steam engine run by the average operator, the motor maintaining uniform speed, corresponding to the displacement of the control lever from off position. Such complete control of the speed of the mill is ideal when steel is entering and leaving the rolls, as there is no change of speed unless the operator so wishes. The motor exerts a constant turning moment in all positions, whereas the steam engine has its maximums and zeros, every revolution. The saving due to the return of the rotative energy of the mill parts to the flywheel gives a means of saving power which is normally lost in steam-driven mills. If 60 per cent of the rotative energy of the mill motor is returned to the flywheel, 60 per cent of this, namely, 36 per cent of the whole, is available again on the mill shaft for active work.

To any plant, whether purchasing power from central station or receiving power from their own power house, the Ilgner system adds an ideal load due to the fact that it is a fairly constant load. If the mill is run to capacity, the power variations will be very slight. The central station load applies in the same way and lends itself, where power is being purchased on a peak basis, to a very low rate. For a large power plant, the increased load does not amount to very much. Taking as an example of this the Hamilton mill: A 1200-kw. generator capacity would easily take care of the load. Where mills are located at various points in the plant, which, from a steam power point of view is inefficient, the Ilnger system eliminates such inefficiency by centralization.

The exceptionally low cost of power is probably the most striking feature of this system, the figures shown being actual figures in no way having been adjusted for cost-keeping purposes. The simplicity of the mill lay-out is another feature which must be considered.

D. M. Petty: I have in mind one or two points I think it would be well to consider in comparing electrical and steam reversing mills. One of the most important points is the flexibility of lay-out. Steam engines, in order to reduce condensation losses, must be near the boiler plant, and while it is possible to locate reversing drives at any position that may be necessary, the fact that mills in recent years are being much more frequently laid out with the idea of reducing the distance that the steel has actually to travel from the soaking pit to the finished product, whatever that may be, is of considerable importance.

The commutators of reversing mill motors I think are probably the most important of electrical problems, because with the reversing mill d-c. drive the commutator is naturally the place where most trouble will be experienced, and most trouble has been experienced. This trouble is not only electrical but mechanical in a good many respects. The number of brushes on the commutator is a direct item in the maintenance charges, but the size of the commutator has a great deal to do with the mechanical troubles which may arise.

So far as the speeds of the motor itself are concerned, they are governed very largely by the speed at which it is desired to run the mill, but the speed of the generators attached to the motor-generator set is not so limited, and I think it is pretty safe to say in regard to d-c. steel-mill motors and generators that the lower the speed, within reasonable limits, the more satisfactory the operation and the lower the operating charges.

The speed of reversal has been emphasized. This should be taken into consideration, but I feel sure that electrical engineers will have no trouble meeting the requirements. It is far more important to insure reliability of operation than to obtain rapid reversal. Size of bearings, method of lubrication, size of shaft and holding of field coils and armature coils in place against heavy shocks are points that stand near the head of the list in importance, in order to make a mill drive reliable.

R. Tschentscher: I would like to correct, first, the statement made by Mr. Hall that the first reversing set was put in at Gary. The first reversing set was in operation, in December, 1905, at Chicago. It was a very small set, about 75 h.p., and the next set of a much larger size, was put in at the same place.

I think there is too much stress being laid on the question of the electrical characteristics of these equipments. As the result of my observation and my experience in the last ten years in operating one of these sets, it is my opinion that the designers should lay more emphasis on the physical arrangement, than on the time of reversal; for example, on the stiffness of the shaft, to prevent oscillations, etc., and on the size of the bearings, to put off as far as possible the time when the bearings must be renewed.

When the first set was purchased in this country, the time of reversal was a subject which was given very careful consideration.

I think that the time of reversal was specified as three seconds. As a matter of fact, there are practically no mills,—there might be one or two small mills—that can use a reversal of three seconds, that is from full speed in one direction to full speed in the other.

Much has been made out of the rapidity of reversal of the steam engine—true, it does reverse very rapidly, but any one who has watched a blooming mill operate will be impressed with the fact that the reversal is fast, but the time consumed from the moment the steel enters the rolls and the rolls grip the piece, and the engine is started up again, is from one to five seconds, and it is a fallacy to put too much stress on the question of the time of reversal when such rapid reversals cannot be used. The piece has to be manipulated, the screw-down operated, etc. The time required for such operations determines the time required for motor reversal.

Any one about to purchase an outfit always has the question of the relative merits of the reversing drive versus the continuous rotation mill, to decide. Efficiencies that may be guaranteed at full load, to me are more or less valueless. What may be called the capacity factor, the average yearly input to the capacity of the outfit, is very low, indeed. I think in continuous rotation mills it will be found that this capacity factor will vary from 15 to 40 per cent and in the reversing mills from 30 to 70 per cent. Figures I have taken show, in a reversing mill operating for twenty-four hours on the basis of the input to the motor of the motor-generator set, divided by the full kw. rating of that motor, that 60 per cent is extremely rare. On that basis, it appears to me that we ought not to spend too much time in attempting to get the last bit of efficiency, but rather get reliability physically, so that when the demands for the mill are increased in times of high pressure and high prices, the outfit will then respond.

H. D. James: I think that we all appreciate that the development of the electrically driven reversing mill is another opportunity to "do it electrically." We all of us believe in electric power, many of us believe in central station power. The use of the electric rolling mill has enabled us to occupy another field with our motor applications.

We have learned a great deal in the past ten years about this reversing drive, and I want to emphasize Mr. Tschentscher's remarks that the time of reversal is not the main essential. It was my privilege to assist in developing the drive of which Mr. Tschentscher spoke, and I wish to add that, he himself, did a great deal to make that drive a success. We started out with the idea that time was one of the most important points, and we ended with other ideas. The tendency now seems to be towards a little more time, and a little more substantial mechanical construction.

F. G. Liljenroth: Having been very closely connected with the European practise of reversing rolling mills during the past ten years, it is with the greatest interest that I have read the

above paper. As Messrs. Sykes and Hall point out, there is quite a difference between the practise in Europe and in the United States, the most noticeable differences being as follows:

Reversible Motor

It seems to be the general practise in the United States to divide the motor, especially the larger sizes, into two units on the same shaft, while the European practise, at least as far as the leading electrical manufacturing companies are concerned, is to build the motor as a single unit, even for the very largest capacities. So, for example, there are to be found in Europe several reversible motors of the same size, that is, with the same torque as the Bethlehem steel motors, which are built in single units, and as far as I know, there is at least one single-unit motor built which has a maximum torque of 240 meter-tons—1,750,000 ft-lb.

The advantages of using single-unit motors are evident: lower first cost and better efficiency, besides the advantages of having to deal with only one commutator, which part is always the weakest in a direct-current machine. Such a single commutator need not be larger than each of the commutators of a two-unit motor, inasmuch as the voltage which is used is as high as from 1000 to 1500 volts and consequently the current is the same as at 2 × 600 volts. There seems to be no disadvantage in using a single-unit motor instead of two. It is true that on account of the higher operating voltage the potential between the brush edges (or rather the voltage which would appear between the brush edges on account of the armature reaction, if this was not compensated for by the commutating poles) is higher than if the machine were divided into two parts, but by correctly determining the ratio of the tangential width of the brush to the commutator pitch, etc., it is possible to limit said potential at maximum peak load to less than $2\frac{1}{2}$ per cent of the operating potential, that is, at 1200 volts to less than 30 volts which is allowed even according to American practise, as stated by Mr. Lamme in his very excellent A. I. E. E. paper dealing with the Commutation of Direct-Current Machines. There are, of course, just as here in the United States other provisions made in order to completely compensate for the potential between the brush edges under all conditions of load. For example, these motors are always equipped with compensating winding, as well as commutating poles, the winding of the latter being placed as close as possible to the armature in order to reduce the leakage field of the commutating pole to the lowest possible value. Furthermore, the commutating poles are tapered and have the same axial length as the armature. In order to avoid a time lag at rapid load fluctuations between the armature current and the commutating field, it has been found advisable to make the commutating poles of laminated iron. The air gap of these poles is made very large, at least one inch, while that of the main poles

is usually about 3/16 in. The armature winding is furthermore provided with numerous equalizing connections, at least one for each slot.

With the above design it has been found that the motors will operate absolutely sparkless, even for the highest peak loads and in watching the commutators of several such machines, they have operated so perfectly that it was impossible to determine whether they carried a load or not. This applied even to peak loads where the non-compensated potential between the brush edges would have been approximately 40 volts. The average voltage between the two commutator bars, that is, the operating voltage divided by the number of commutator bars between two brush positions does not, for such machines, exceed 20 volts which must be considered a conservative value.

Generators

It is the general European practise to use two generators of from 500 to 750 volts (usually 600 volts) connected in series and consequently the same practise as in the United States. For the newest installations the speed is, however, considerably higher than was the case some years ago, and which still seems to be maintained in the United States. But this, only refers to the modern installations which were completed shortly before and after the beginning of the war. Sufficient time has elapsed since these motor-generator sets were installed and the results obtained have clearly demonstrated that such speeds are entirely satisfactory and safe, and, as far as Europe is concerned, they have caused a revolution in the design of such machines. The first cost is considerably lower, while the space required is also much lower and the efficiency higher. Comparing such a flywheel motor-generator set with the older designs, one is immediately astonished by its small dimensions. The Bethlehem Steel set could have had a speed of at least 514 instead of 375 revolutions, that is, at 60 cycles the induction motor should have had 14 poles.

With the higher speed the motor generator can be built much smaller and this particularly refers to the flywheel. For a certain WR^2 it is evident that the mass of the wheel and consequently also its weight can be the same, independent of what speed is chosen, if only the peripheral speed is maintained constant. In most cases, however, the diameter of the flywheel is limited by shipping facilities to about 4 meters—13 ft. and the peripheral speed by the permissible stresses at maximum runaway speed, this usually being taken as 25 per cent above normal speed. The stresses should in no part in the wheel at its runaway speed be permitted to exceed 10kg. per sq. mm. or about 14,000 lb. per sq. in. which values at normal speed would correspond to about 9000 lb. These values are, as seen, very low and conservative, and it is not necessary to use any especially expensive material in the wheel, but only ordinary

cast steel with an elasticity of 40,000 and an ultimate strength of approximately 70,000. Regardless of these low stresses, it is possible, by using a suitable design of flywheel, to go to a peripheral speed of as high as 430 feet per second and still not exceed a stress of 14,000 lb. per sq. in. at runaway speed. From the above it follows that the lowest speed which should ever be used for such a flywheel should be:

$$\frac{430 \times 0.8 \times 60}{13 \times \pi} = 500 \text{ rev. per. min.}$$

The largest generator which can be built at this speed has a maximum load, that is, peak load, of about 4300 kw., this being under the assumption that the peripheral speed of the armature is not to exceed 150 feet per second and the average voltage between the two commutator bars not to exceed 20 volts and that at peak load, amperes $\times$ armature conductors per cm. circumference is about 800.

The Bethlehem motor requires approximately 8500 kw. and it follows, therefore, that its motor generator could readily have been built for 500 revolutions with two series connected generators each for 600 volts. The weight of the flywheel could have been reduced in proportion $\left(\frac{375}{500}\right)^2$ or to approximately one-half and the flywheel effect would still have been retained. This is under assumption, that the diameter of the Bethlehem flywheel is about 13 feet. It is possible, however, that there are other reasons for using the low speed and it would be interesting to obtain information in regard to:

1. The largest permissible diameter of the flywheel limited by transportation facilities.
2. The percentage of runaway speeds which are usually specified.
3. The corresponding permissible stresses in the flywheel as well as the properties and the material which is used.
4. The corresponding peripheral speed whose relation to the stresses is dependent on the design of the flywheel.

Excitation

As far as the excitation is concerned, the European practise comprises what is known as the "indirect" regulation, that is, the rheostats or controllers are not inserted in the generator or motor fields, but in the fields of the exciters. The exciters are used, one for the generators and one for the motor, the voltage of the exciters being regulated. The exciters are, therefore, in turn magnetized from a third exciter which consequently can be very small, working normally as a shunt generator with constant potential. These three machines are driven by a common small induction motor.

The advantages of this scheme are: smaller equipment,

lower first cost and especially greater reliability as far as the rheostats and controllers are concerned, in that the currents which have to be handled are only from one to two per cent of what would be the case if the "direct" excitation were used. For rolling mill service it is evident that the control equipments have to withstand very severe service both electrically as well as mechanically on account of the rapid breaking of comparatively large magnetic energies and also due to the fact that they are in almost continuous service. The advantages of smaller equipments which are obtained by the smaller apparatus used with indirect excitation are, therefore, obvious. The excitation will be just as rapid as by the direct method, on account of the fact that the magnetic energy stored in the small exciter fields is negligible compared to the large machines.

The compounding is usually made in the way that the main poles of the generators have an opposing series winding which therefore does not have to be reversed. Against this practise it may be argued that an assisting compound winding on the motor would be better, inasmuch as the torque will be increased by strengthening the field. This, however, is more or less an imaginary advantage, as for machines of this kind the saturation curve at normal speed is so flat that a large increase in the field current creates a very small or almost no strengthening of the field.

Concerning the safety devices and the arrangement of the automatic load regulation, etc., the European practise involves several quite interesting departures from the practise in the United States, but space does not permit of further discussion of this subject.

Brent Wiley: It would be well to consider the blooming mill equipment from the standpoint of the entire mill drive, as practically every steel plant is composed of finishing or semi-finishing mills, as well as blooming mills.

During the last eleven years more than three hundred large motor units, totalling over 500,000 h.p., have been installed to drive the main rolls of steel mills.

The following list gives the electrically driven reversing blooming mills installed, and on order in the United States and Canada. The majority of the equipments have been purchased during the last few years.

			Installed
—	Blooming Mill	—Algoma Steel Co. Sault Ste. Marie, Can.	1911
34 in.	" "	—Steel Co. of Canada, Hamilton, Ont.	1913
34 in.	" "	—Central Steel Co., Massillon, Ohio,	1914
35 in.	" "	—Bethlehem Steel Co. Bethlehem, Pa.,	1915
35 in.	" "	—United Steel Co., Canton, Ohio,	On order.
40 in.	" "	—Inland Steel Co., Indiana Harbor,	" "
32 in.	" "	—Inland Steel Co., Indiana Harbor,	" "
40 in.	" "	—Illinios Steel Co., Gary, Ind.	" "
40 in.	" "	—National Tube Co., Lorain, Ohio	" "
34 in.	" "	—Chattanooga Steel Co., Chattanooga	" "
35 in.	" "	—Mark Mfg. Co., Indiana Harbor,	" "
34 in.	" "	—Ashland I. & M. Co., Ashland, Ky.	" "
34 in.	" "	—Keystone Steel & Wire, Peoria, Ill.	" "

REVERSING MOTOR EQUIPMENTS—FOR OTHER TYPES OF MILLS.

		Installed
30 in. Universal Plate Mill	Ill. Steel Co., S. Chicago,	1908
Plate Mill	—Am. Sheet & T.P. Co., Gary, Ind.	1910
" "	— ditto	1910
28 in. Structural Mill	—Inland Steel Co., Indiana Harbor,	On Order
27 in. Universal Plate Mill	Mark Mfg. Co., Indiana Harbor	" "

The principal object of the earlier installations was to utilize cheap power and the incidental advantages possible were not taken into account. Experience has demonstrated that motor drive has many favorable features which are of economic value in not only the every day operation of the mill, but assist most materially in the development of the method of operation.

Motor drive gives the greatest latitude regarding the arrangement and design of mill and of the entire plant. Motors can be designed with either high, intermediate or low speed, and with a wide variation in maximum or pull-out torque. Adjustable speed motors give a wide range of operating speeds, with very economical operation of mill, either for constant torque or constant horse-power requirements. The regulation of the alternating-current motor is very close, even under a wide range of load, varying only about two and one-half per cent from light to full load. It is capable of standing heavy overloads frequently for comparatively long periods, without undue strain or deterioration. The ease with which power readings can be made instantaneously and for any desired period is of great value in compiling records to ascertain the effect and value of any change that is inaugurated in the development of the mill design.

The general experience in the operation of a new mill is that the results obtained, after a few years, are radically different from the ideas of the possibilities and expectations of what could be accomplished when the design was first conceived. In the majority of cases it is necessary to make a number of assumptions regarding the possibilities of each particular portion of the mill, including capacity of heating furnaces required, permissible reductions per pass, speed of rolling, size and shape of product most desirable from the standpoint of trade demands. The mill is developed as more information is obtained regarding these factors, and the incidental advantages of motor drive have played an important part in accomplishing the most satisfactory results in reversing blooming mills, as well as other types of rolling mills, as the general advantages are the same for all types of motor equipment.

First Cost

It is assumed that the plant is designed with motor drive for the blooming mill, finishing mills, and for the auxiliaries.

The average load on the electric power station to drive a reversing blooming mill with maximum peaks of 15,000 to 20,000 h.p. is approximately 3000 to 3500 h.p., with variations of not more than 15 per cent during the active rolling period of the

mill. The station capacity will be divided approximately 80 per cent for motors of auxiliary machines and finishing mills and 20 per cen tfor the reversing mill equipment. In other words, it will require a comparatively small increase of power plant to provide for the blooming mill work which is quite a contrast with the requirements in an addition to a boiler plant for a steam engine-operated blooming mill.

Furthermore, the addition of a very uniform load assists in equalizing the total plant load, and thereby increases the efficiency of operation.

The use of central station power is also a very material factor in reducing the first cost, and many steel plants are taking advantage of this point as well as of other favorable factors which purchased power affords. At present, there are more than fifty steel plants obtaining part or all of their electric power from central stations, and are using a total of approximatley 425,000,000 kw-hr. per year, which is approximately 18 per cent of the total electric power required per year by the iron and steel industry.

ECONOMY OF OPERATION

There is more economy of operation to be gained by the electrification of the reversing blooming mill than of any other type of mill. In the case of the averaging existing steam engine-driven mill, the steam consumption can be reduced fully fifty per cent by use of motor drive. This comparison is made on the basis of using electric power as furnished by steam turbines at approximately 5000-kw. capacity. Undoubtedly there are many cases where the gain would be even greater than this, but on account of the limited test data available regarding the steam requirements and general analysis of plant conditions, it has been difficult to establish these facts definitely.

H. S. Page: Analysis of the sequence of operations during rolling might serve to bring about closer unanimity of opinion in regard to the permissible time of reversal. The actual reversal occurs during the time the metal is out of the rolls between passes: is from a comparatively low speed in one direction to about the same, or lower speed in the opposite direction, and can easily be accomplished while the metal is being returned to the rolls. After the metal enters the rolls it is of the utmost importance to have a driving motor capable of accelerating the mill to the maximum speed of the pass just as quickly as possible. The retarding action of any device installed for the protection of the motor should be carefully considered; as the function of most of these auxiliary devices is to prevent rapid acceleration and thus limit the output of the mill.

A few comments might be added on the subject of general design of reversing mill apparatus which is treated at some length in the paper. Generally speaking it is permissible to sacrifice efficiency to a slight degree in order to gain more rapid acceleration and for this reason it seems advisable to work all

magnetic and current carrying material in the motor armature at the highest possible densities in order to reduce the stored energy to a minimum, the voltage being determined by the most economical arrangement of armature conductors and commutator segments. A decided advantage is gained by designing the motor with a view to cooling by means of forced ventilation. Valuable protection of commutators and brushes from the sharp steel mill dust and grit, as well as insurance from burnouts caused by deposits of this same material can be obtained by blowing sufficient thoroughly washed air through the motor for the complete ventilation of the dynamo room. As mentioned, before, it would seem advisable to let the voltage of these equipments be fixed by conditions governing the design of the motor rather than choose a voltage best suited to the generating set. The speed-voltage curves submitted with the paper apply fairly well to present day design but as the tendency is toward higher speed generating apparatus, it is questionable whether they will apply a few years hence.

The rapid fluctuating speed and load conditions required by the cycle of operation of this type of equipment makes the question of rating, especially of the driving motor a rather vexed one. A very convenient working basis for heating can be taken as the maximum continuous safe load capacity at full field on the motor and maximum continuous generator voltage. If some such rating is established and the heating properly calculated from the rolling cycle for each installation much of the trouble which has been met in the past with electrically driven rolling mills will be avoided. Of course in addition to this it is necessary to make proper allowances for the range in load and speed as well as to carefully consider the mechanical stresses which are brought about by the rapidly fluctuating load conditions.

Peter Lindemann: There is one point in my mind which the schematic diagram shown in Fig. 3 of the paper does not make entirely clear.

It may be that there are other controlling devices used which are not shown in this diagram, and which will prevent the starting of the direct-current motors while the generator field rheostat is in neutral position, for it seems to me that the shifting of the brush holders on one of the direct-current separately excited generators would cause voltage to be built up on the closed motor circuit.

It would be interesting to know what precaution, if any, has been provided against such an occurrence.

Alex. Gray: One of the previous speakers brought up the question of the speed of the flywheel motor-generator set, and stated that whereas we use a speed of 375 rev. per min., European engineers have gone up to 500 rev. per min. for the same horsepower output. To me this would indicate one thing only, namely, that Eurpoean engineers work much closer to the limit than we care to do on this side.

I once made the remark that there were limitations in the design of electrical machinery, and was told by a well known operating engineer that such limitations did not exist, and that as soon as the operating engineer demanded anything, the designing engineer found a way to overcome his limits and supplied the demand.

Mr. Hall in his paper has drawn attention to the fact that for each speed there is an output rating that cannot be exceeded unless the engineer is looking for trouble. This may be explained as follows: Taking a machine of given diameter, there is a safe maximum speed at which this machine may be run, and the output is then limited only by the length of the armature core. As this length is increased, the voltage generated in each turn of the armature also increases until, when a value of about 6 volts between adjacent segments is reached, interpoles become necessary. With inter-poles supplied, the machine may be further lengthened until, when a value of about fifteen volts is reached between segments, the machine becomes sensitive to changes in load and is liable to flash over. Compensating windings must then be supplied, if the output is to be further increased.

Evidently, then, the 500-rev. per min. European machine is run either with a greater peripheral velocity, or with a greater value of voltage between segments than in the case of the 375-rev. per min. American machine. From the fact that they are designed closer to the limit, much more care is necessary in the construction of the apparatus, so that the machine is not necessarily cheaper.

In regard to the rating of the motors, it must be clearly understood that while the motors in question have a rating of 10,000 h.p., at 100 rev. per min., they would become hot with a continuous output of about 4000 h.p. On the other hand, if the machines were large enough to dissipate the loss corresponding to a 10,000-h.p. load, they would have become so long as to operate badly with regard to commutation.

It is, therefore, rather hard to decide how they should be rated, because they are designed as 10,000-h.p. machines so far as commutation is concerned, and as 4000-h.p. machines so far as heating is concerned. Since the former is the more important limitation of the two, it seems reasonable to give them a rating of 10,000 h.p. maximum.

With regard further to the rapidity of reversal of the generator voltage, it is of interest to note that, since the machines have compensating windings, the air-gaps can be small, and the shunt excitation be almost negligible. It is, therefore, quite within reason to put a non-inductive resistance in series with the field-coil circuit so as to reduce the time constant of this circuit and thereby allow the field to build up rapidly; and this would not reduce the efficiency of the machine to any appreciable extent, and, moreover, would allow the rate at which the machine builds up to be adjusted. It would seem from the discussion, however, that the machine reverses as rapidly as the mill engineer desires.

Wilfred Sykes: The discussion by Mr. Pauly indicates lack of experience with this type of apparatus. The question of rating has been given considerable thought by engineers designing reversing mill equipments, both here and abroad, and it has been the practise to rate reversing mills on the maximum operating peak loads as it is these loads that fix the size of the apparatus, and not the continuous capacity based on heating. These loads do not represent the absolute maximum capacity of the machines without injury, but are the peaks that are ordinarily carried during the operation of the mill.

Mr. Pauly's remarks regarding the similarity of the reversing rolling mill and the mine hoist motors are correct as far as the general system used is concerned, but the operating characteristics of the reversing rolling mill motor, and the control problems are entirely different, and much more difficult than those of the mine hoist. The shocks which the reversing mill motor is subjected to are very much more severe than those of the non-reversing mill motor where the conditions are comparable, such as, for instance; the three-high blooming mill compared with the two-high blooming mill. In such cases the continuously running motor has a flywheel between it and the mill, and the shocks on the parts of the machine are very much less than with the reversing motor where the flywheel effect is reduced to a minimum.

Mr. Pauly's remarks about the speed of operation are answered very well by the discussion of Mr. Tschentscher. The same opinion was held ten years ago regarding the necessity for high rate of speed change, but after practical experience obtained with electrically driven mills it was obvious that extreme steps were not necessary to obtain high rate of reversal, and when Mr. Pauly has gained some actual experience with these mills, no doubt, his views will change.

The question of size of motor shaft, and upon which Mr. Pauly places so much stress, seems to be catering rather to the old idea of making a part massive without the appreciation of the conditions under which it operates. It is obviously useless to make the shaft many times stronger than some other part of the machine which is just as liable to be broken, and in designing equipments it has been our object to obtain the accumulated experience of motor and engine builders for this type of mill. A shaft diameter out of all proportion to the output of the equipment, or the size of the mill may be an excellent talking point in selling apparatus to an ignorant customer, but is not good engineering.

Regarding the discussion of Mr. Petty. It is not feasible to reduce the speed of the generator below certain limits, due to the fact that the flywheel diameter is limited by transportation facilities, and the flywheel effect necessary might mean prohibitive weights with speeds too low for economical design.

Mr. Lilgenroth brings up a number of points regarding the

design of European compared with American reversing mills. The question of using one instead of two motors for the large equipments has received a great deal of consideration, and it was with a full knowledge of the European practise that the equipments now being built were designed with double motors. The question of safety to attendants is one on which a great deal of stress has been placed by mill operators, and there was a very great objection to the use of voltage higher than 600 across an individual machine. In the United States we must also face less skillful attendants, and the use of a 600-volt machine with 1200-volt insulation, such as the Bethlehem machine is, gives us a greater factor of safety than would be possible if we used single motors with, say, 1500 volts on the windings. The design features brought out, having been found desirable in Europe, are all incorporated in the machines which have been built.

The question of generator speed is one that has been given a good deal of thought, and it might be of interest to mention that the 500-revolution generators running at the Steel Company of Canada's plant repeatedly carry loads of 5000 kw. each, and it is quite possible to build generators for 500 revolutions to supply power to the motors at Bethlehem. On the other hand, using a speed of 375 r. p. m., there is greater leeway, and a greater margin could be obtained to cover the uncertainty of operation which was a factor on the Bethlehem installation. This mill was installed for rolling a very wide range of products, and different classes of steels, and it was practically impossible to predict before hand just how much power would be required. For this reason a conservative design was adopted, the wisdom of which has been shown by the operating conditions of the mill, since installed.

Regarding the question of flywheels, we have found it desirable to limit the operating peripheral speed to approximately 300 ft. per sec., although the stresses at this speed are very low. This is due to the uncertainties as to the quality of metal obtained in castings. The conditions in the United States are very different from those in Europe where cast steel wheels, for higher speeds, can be readily obtained.

Regarding the question raised by Mr. Lindemann, provision is made in the controller for the generator fields to prevent the motors being started in the way he mentions.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

MOTOR EQUIPMENTS FOR THE RECOVERY OF PETROLEUM

BY W. G. TAYLOR

ABSTRACT OF PAPER

The work of drilling, pumping and cleaning oil wells is very successfully handled by slip-ring induction motors. With the cable-tool method of drilling a special arrangement of controllers and resistance is used to obtain the required fine speed control. Similar motors are used for both this and the hydraulic rotary method.

Pumping and cleaning, which includes 'pulling' the rods and tubing, are in most cases all performed by the same motor which may be a 'Y-Delta' or a two-speed machine, depending upon operating conditions. Both of these motors are double-rated, the low rating being used for pumping and the other for pulling and cleaning. High efficiency is essential on the pumping duty and high torque for the heavy work of pulling and cleaning the well. For both types of motors special control features are used to properly protect the equipment as well as to make it most convenient for the operator. For wells pumped by jack-rigs, a portable hoist is employed to pull rods and tubing.

This paper presents data covering the horse power requirements and kilowatt-hour consumption for the various operations in drilling and maintaining producing oil wells.

THE GRADUAL decline in production which is characteristic of all oil fields as well as the great losses sustained with the usual methods of steam operation are the factors which generally furnish an incentive to the producing company to electrify its wells. The economy thus gained often gives the wells a longer lease of life, as it enables them to be pumped at a profit at a lower daily production than would otherwise be possible. In most cases economy is only one of the several advantages of motor drive which are taken into consideration, these including greater reliability, simpler and more accurate speed control, steadier speed, greater safety and lower insurance rates than with other types of motive power. These advantages on any motor application are too well known to warrant more than incidental mention.

The choice between alternating and direct current is generally determined by the available power supply and for this reason

induction motors are used on nearly all electrically operated wells. Several isolated generating plants are in operation which were installed for the purpose of carrying an oil well motor load and which were designed for alternating current because of the inherent superiority for this service of an induction motor over a direct-current machine. Although the latter may at first appear to be a more advantageous type of motor on account of the speed variation obtainable by field control without material reduction in efficiency, yet when it is taken into consideration that oil well motors must often carry sudden and severe overloads and be frequently reversed at full speed, and are subjected to much abusive handling by unskilled operators, the overload limitations of a direct-current motor prove to be a severe handicap. A more complex control is necessary to protect the motor, and if this is not provided the depreciation of the commutator is rapid on the heavy duty.

There is a large number of varied operations which oil well motors are called upon to perform, and these fall naturally into three groups; drilling, pumping and cleaning. The process of drilling a well includes the operations of handling the drilling tools and the casing with which the hole is lined, and of removing the drillings by bailing or hydraulic flushing. The work of pumping includes such operations as are occasionally necessary to free the pump and valves from sand. The cleaning of a well is a process which varies with the conditions encountered. It is always necessary, however, to pull out the rods and tubing, which is known as 'pulling' the well. The accumulated sand and sediment are then removed by bailing or hydraulic washing, and may first require loosening up with a light 'string' of drilling tools. Swabbing is sometimes done to improve the flow of oil.

The most logical method of applying motors to these operations is to use a different machine for each of the three groups, as this not only involves the least complication in design, but also requires the minimum investment by the oil company, consistent with efficient operation. It has, however, been found more practical in most cases to use one motor for the drilling process and another for all the work involved in pumping, pulling and cleaning the wells.

Drilling

The two methods of drilling which are in general use in the United States are the standard or cable-tool method, and the

hydraulic rotary method. The former employs a walking-beam from the end of which a heavy stem and bit are suspended by a steel wire or manila rope. These churn the hole by the up-and-

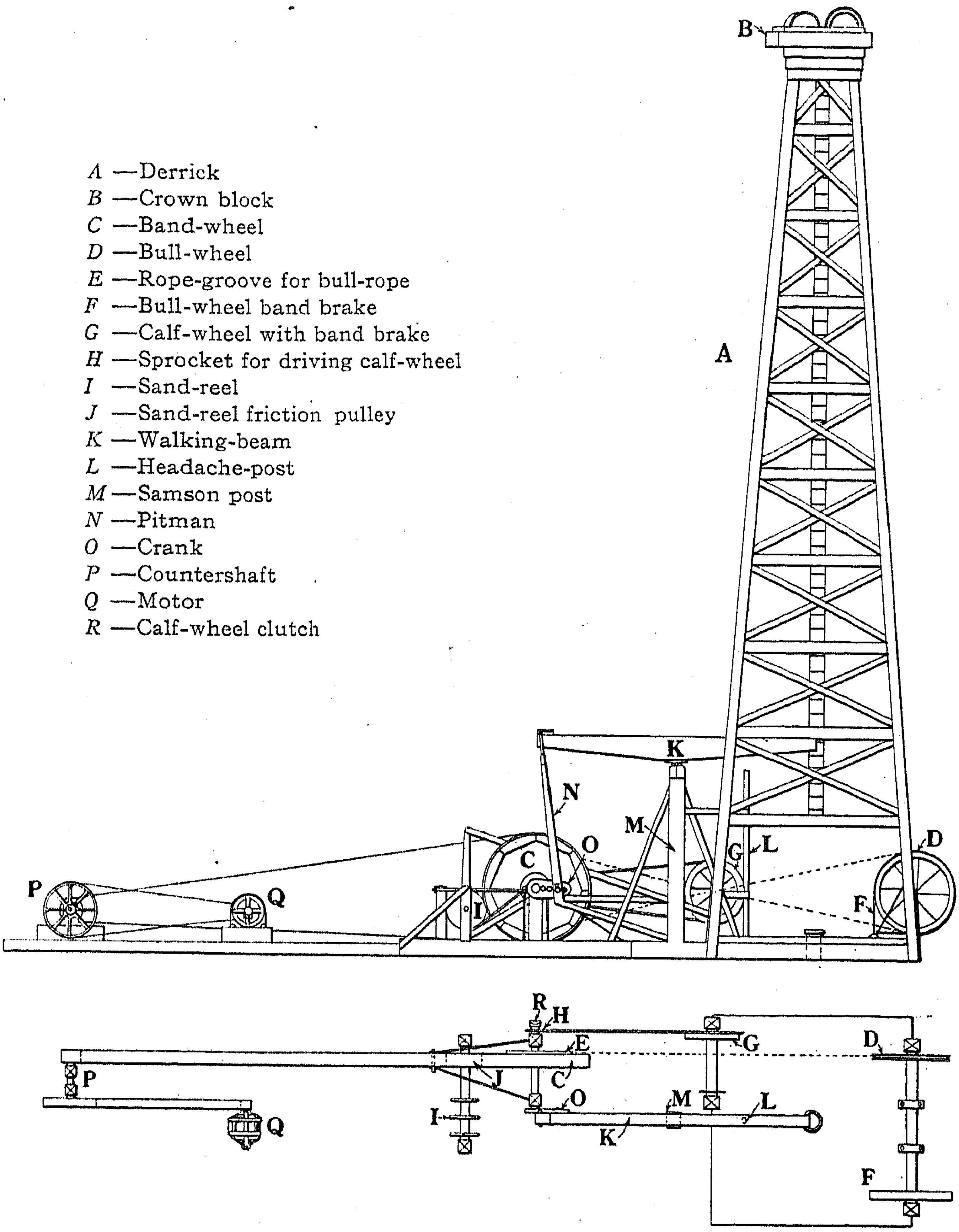


FIG. 1—ELEVATION AND PLAN OF MOTOR-DRIVEN STANDARD CALIFORNIA OIL WELL RIG

down motion imparted by the beam, the strata thus being penetrated by percussion. The drillings are mixed with water in the hole and are removed at intervals by a ' sand-pump ' or bailer. As the hole deepens, iron or steel casing is inserted in approxi-

mately 20-foot lengths, screwed together, but may not be used where there is no danger of caving.

The arrangement of the standard motor-operated drilling rig used in the California fields is illustrated in Fig. 1. For actual drilling work the drilling line is suspended from the end of the walking-beam, but the hoisting of the tools is done by the bull-wheel, rope-driven from the band-wheel, with the walking-beam disconnected from the crank. The drilling line is wound on the bull-wheel shaft and passes over a sheave on the crown block. Casing is handled in a similar manner by the calf-wheel, with the addition of a block and tackle having from seven to nine lines. The bailer, which is a long tube with a check valve at the lower end, is hoisted by a separate line wound on the sand-reel, the latter being run from the band-wheel by friction drive. On rigs

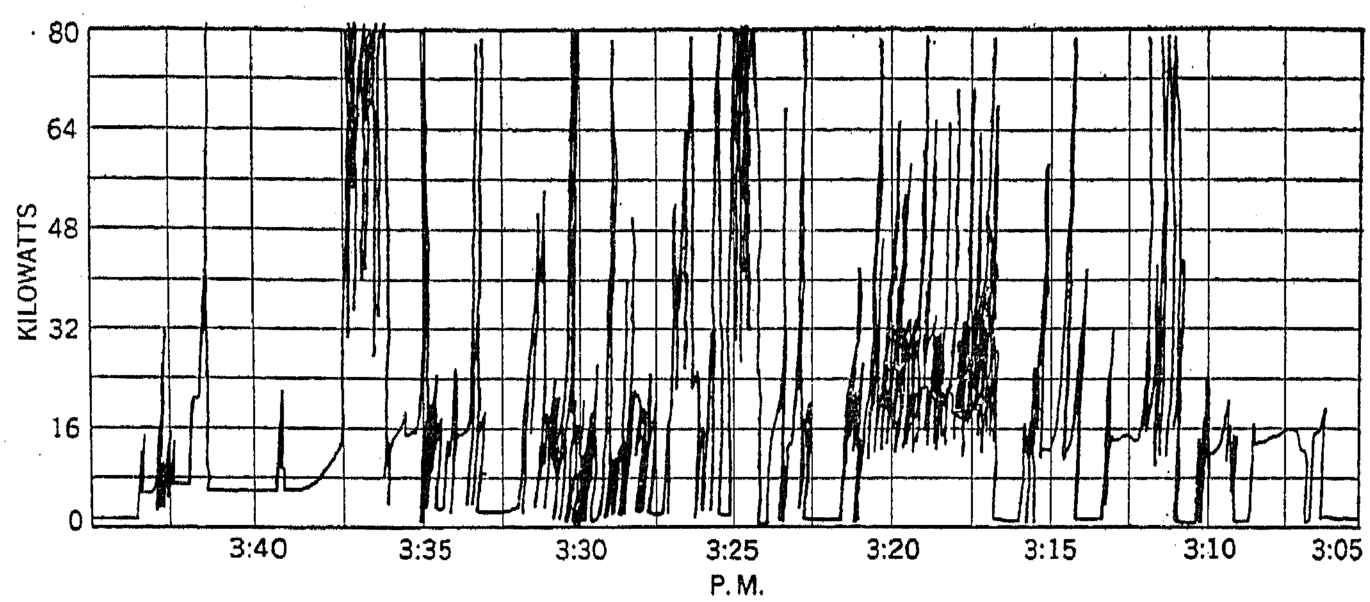


FIG. 2—GRAPHIC RECORD OF POWER REQUIRED FOR "SPUDDING IN" CASING IN A CALIFORNIA OIL WELL

not having a sand-reel the bull-wheel is employed for this purpose.

The heaviest work encountered by the drilling motor is the manipulation of the casing. It is frequently necessary to repeatedly raise and lower a string of casing a few feet for long periods in order to relieve the friction caused by pressure of the surrounding strata, and thus work a clear passage. This is known as 'spudding in' the casing. It requires continued reversing of the motor under heavy load, and is very well illustrated by the graphic record shown in Fig. 2, which was made on a 50-h.p. equipment. It is important that the motor should have ample margin in torque to accomplish this without overheating or stalling, as failure to free the string of casing compels the operator to continue with a smaller diameter. Occurrences of this

kind would result in the minimum diameter being reached at too shallow a depth and thus render it impossible to continue drilling to the oil sand.

The other drilling operations are lighter work for the motor

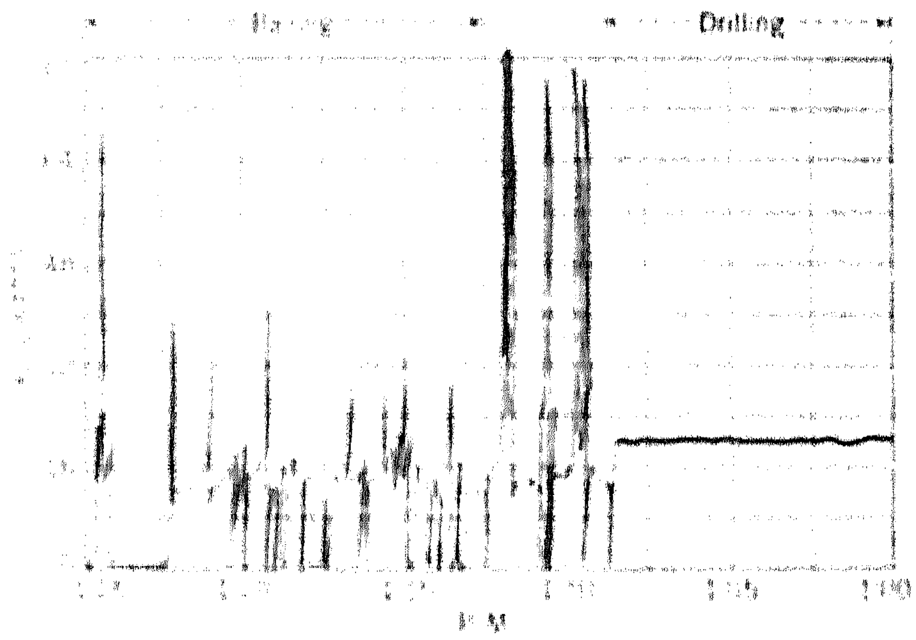


FIG. 3—GRAPHIC RECORD OF POWER REQUIRED FOR DRILLING AND BAILING WORK IN A CALIFORNIA OIL WELL

as will be seen by a comparison of Figs. 2 and 3. The power demand from the motor to merely swing the tools during actual drilling by the cable-tool method is fairly steady, as Fig. 3 shows, but it is interesting to note that this demand becomes less as the well grows deeper. Fig. 4, which represents this

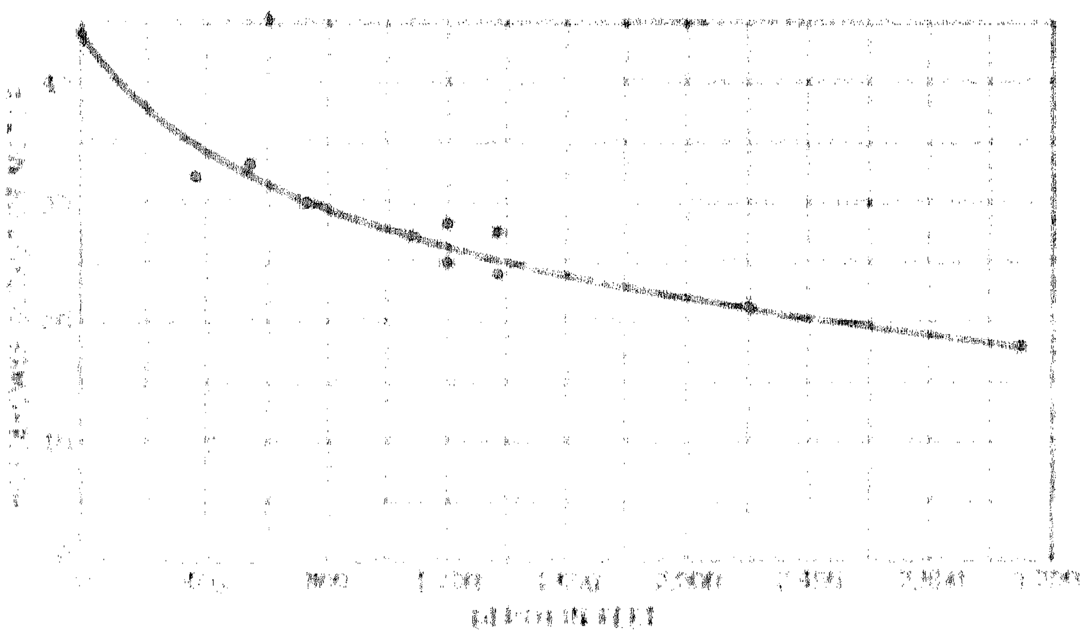


FIG. 4—HORSE POWER REQUIRED FOR SWINGING STANDARD CABLE TOOLS IN DRILLING A 3100-FT. OIL WELL IN WEST VIRGINIA

fact, shows a curve plotted from readings taken during the various stages of drilling a 3100-ft. well. The point may be explained by the facts that as the well grows deeper the drilling tools used are smaller in diameter and lighter in weight, and a larger amount of water is usually carried in the hole.

After a well has reached a depth of 300 or 400 ft., the amount of energy required per hundred feet for all drilling operations by the standard method increases with the depth of the well. Although it has already been pointed out that the power necessary to swing the tools grows less, on the other hand the length of time required for bailing increases in proportion to the depth, with little or no reduction in horse power, and the dash-pot action in pulling out the bailer becomes greater due to the larger amount of fluid carried in the well. It is also usually necessary to work the casing more frequently as the depth increases, in order to prevent it from 'freezing' or sticking. Both of these conditions cause a considerable increase in energy consumption. Furthermore, progress becomes slower as the well deepens. Therefore considering all of these points, it is apparent that the kw-hr. consumption will increase more rapidly than in direct proportion to the depth, and actual results plotted in Fig. 5 for a 2060-ft. well indicate that it varies approximately as the square of the depth, barring accidents and extensive jobs of 'fishing' for lost rope, tools or damaged casing. The individual points also plotted in Fig. 5 represent the total power consumption recorded in drilling other wells of various depths. They check as closely as could be expected with the record for the 2060-ft. well at a corresponding depth. Under the usual conditions encountered, and without any great amount of bad luck in the drilling work, the average daily power consumption when the motor is in use, is about 230 kw-hrs., but it will vary on different days from approximately 135 to 400 kw-hr., depending upon what class of work is being done.

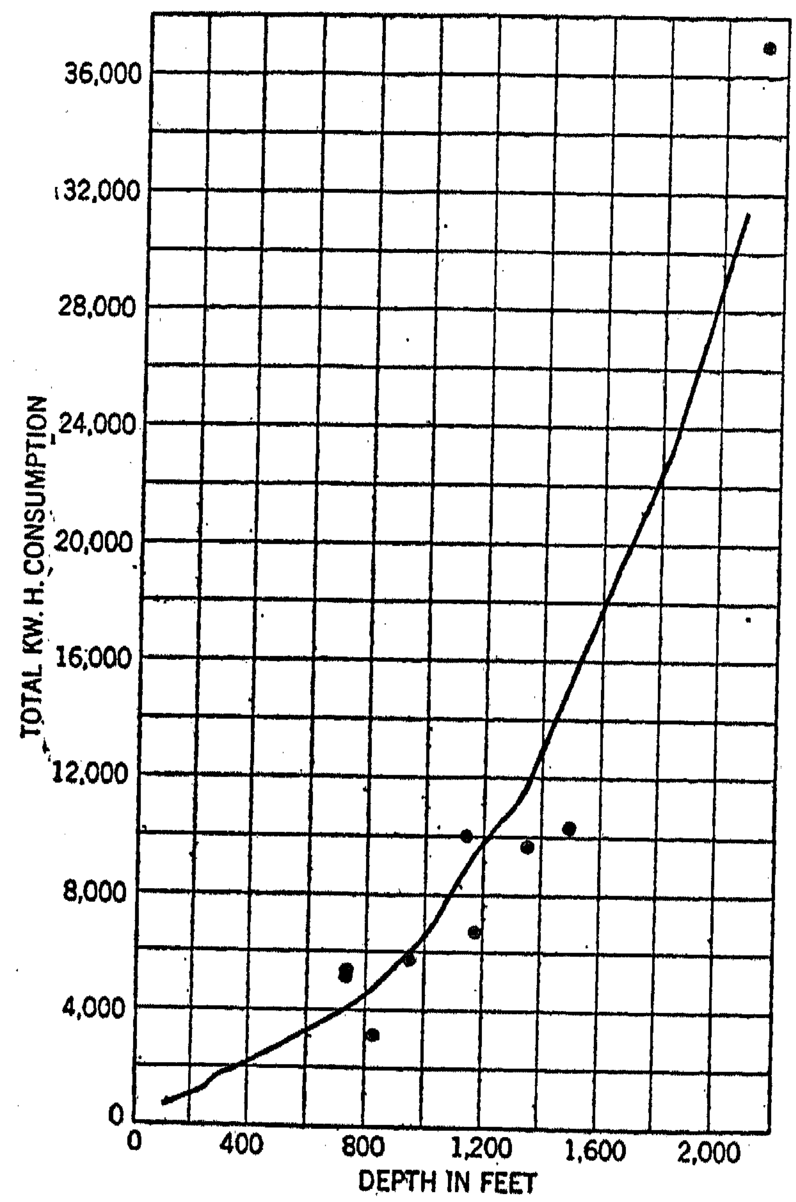


FIG. 5—CURVE OF TOTAL POWER CONSUMPTION COVERING ALL OPERATIONS IN DRILLING A 2060-FT. OIL WELL BY THE STANDARD CABLE-TOOL METHOD. THE INDIVIDUAL POINTS PLOTTED ARE THE TOTAL RECORDED KW-HR. ON VARIOUS OTHER WELLS

The most successful drilling motors now used in American oil fields are of the slip-ring induction type with secondary resistance control arranged for reversing duty. A capacity of 50 h.p. is usually sufficient for wells not exceeding 2500 ft. in depth, though cases have occurred where 75 h.p. was necessary on wells from 2000 to 2500 ft. in depth, as well as on the deeper ones. The belted arrangement with a countershaft has proved the best, as the severe service has rapidly put out of commission the various types of gear drive which have been tried.

In the cable-tool method of drilling, the beam must overspeed and allow a relatively free drop of the tools on the down stroke to obtain the most effective blow; the motor to accomplish

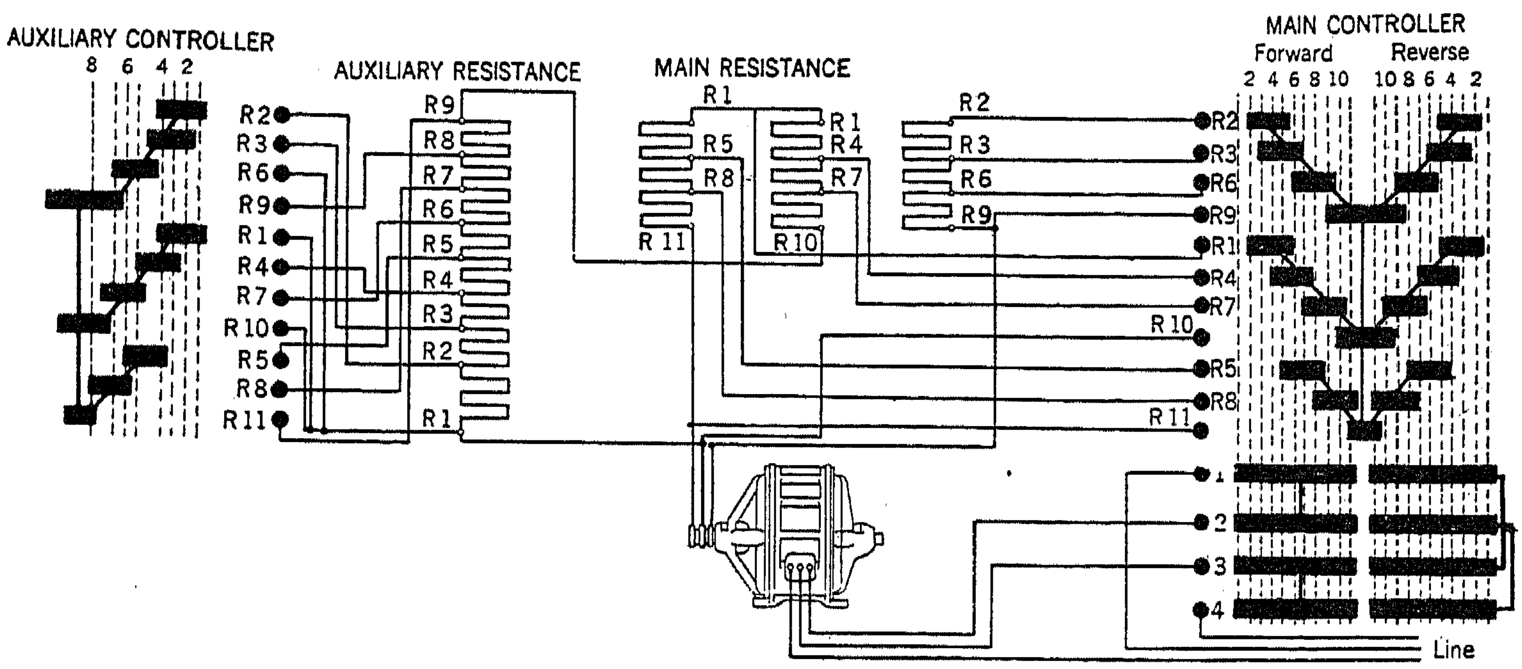


FIG. 6—CONNECTIONS FOR MOTOR EQUIPMENT FOR STANDARD CABLE-TOOL DRILLING

this must therefore slow down on the up stroke and speed up on the down stroke. This is quite successfully accomplished by so proportioning the pulleys that the motor will have some secondary resistance in circuit when running at the correct drilling speed. There is also required a very fine adjustment of speed to make the movement of the beam accord with the natural period of vibration of the drilling line due to its elasticity. Failure to obtain the exact speed results in deadening the movement of the bit and may strain the line and rig dangerously. A suitably designed liquid rheostat would be an ideal method of control if it received the necessary attention and a good quality of water, but unfortunately neither of these can be given it under the usual conditions in the oil fields and so drum controllers have been adopted, connected as shown in Fig. 6. The main

controller gives a coarse variation of speed and reverses the motor, and the auxiliary controller provides a means of obtaining fine speed control between the points on the main controller for either direction of rotation. These controllers are each operated by wire ropes extending to the headache-post in the derrick, the arrangement in this respect being similar to the method of throttle control employed with engine-driven rigs. A complete installation is shown in Fig. 7.

Drilling by the rotary method is accomplished by boring rather than by churning the hole. The drilling bit is supported at the lower end of a column of pipe which is held and rotated by a turntable. The latter is driven through a series of chains and gears. A hoisting drum, which is clutched in when desired, is also provided for handling the drilling stem and casing. The drillings are washed out by a stream of thin mud circulated by the 'slush-pump' down through the rotating column of pipe and up outside of it, thus causing the pipe to turn more easily and preventing caving by plastering the sides of the hole with mud. Only a few wells have so far been drilled by this method with motor drive, but excellent results were obtained with the same type of motor as is used for the cable-tool method. A fairly close speed adjustment is needed to operate the bit at the most effective cutting speed, inasmuch as the latter varies with the nature of the strata encountered.

Pumping, Pulling and Cleaning

Pumping is accomplished by means of a deep-well pump of the plunger type which is lowered on the end of a string of tubing to a sufficient depth to insure ample submersion. The plunger is operated by jointed iron or wooden rods extending down within the tubing and attached to the end of the walking-beam or to a pumping-jack operated from a central power-head. The flow of oil through the tubing to the surface is governed by suitable check valves in the barrel and plunger of the pump.

The rods and tubing must be frequently removed to clean out the well or to replace broken or worn parts, and the bull-wheel is then employed except where the use of pumping-jacks makes a portable hoist necessary. Rods are pulled with a single line, but a block and tackle with two or three lines is necessary for the tubing. Both are removed in lengths approximately 60 ft. long which usually consist of three 20 ft. sections screwed together. Bailing, light redrilling, washing or swabbing may be employed in the process of cleaning.

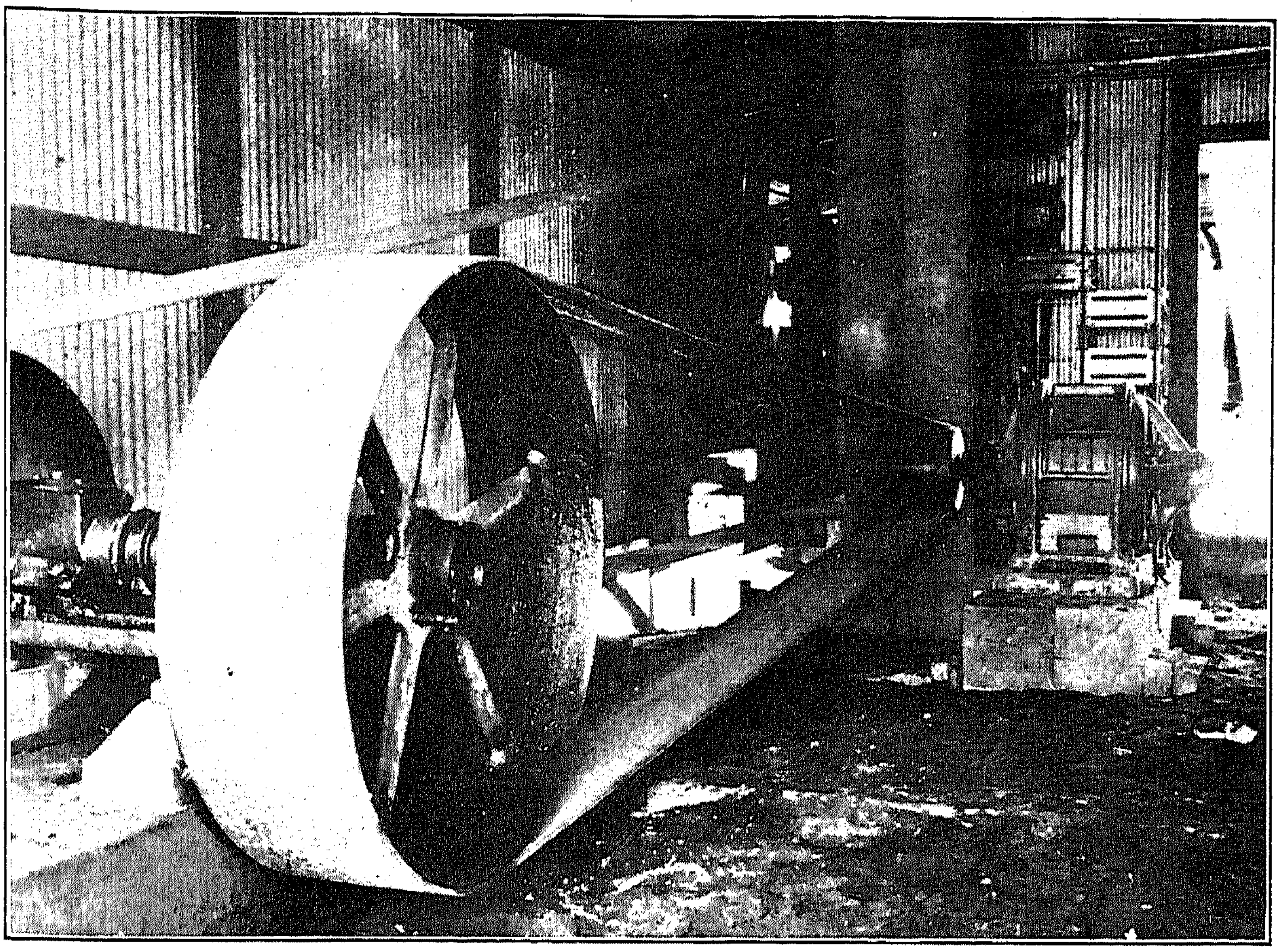


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FIG. 7—A 50-H.P. DRILLING MOTOR OPERATING CABLE-TOOLS ON A STANDARD CALIFORNIA RIG

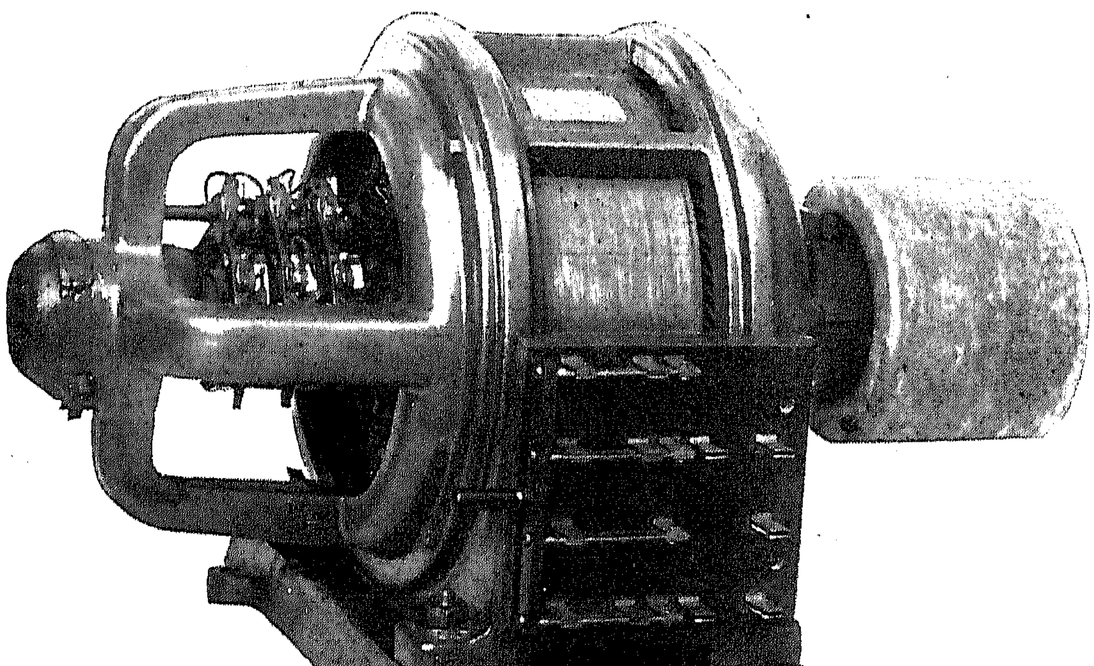

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FIG. 9—TWO-SPEED 25/8-H.P. 1200/600-REV. PER MIN. THREE-PHASE, 60-CYCLE, 440-VOLT OIL WELL MOTOR FOR PUMPING, PULLING AND CLEANING WELLS OF MODERATE DEPTH

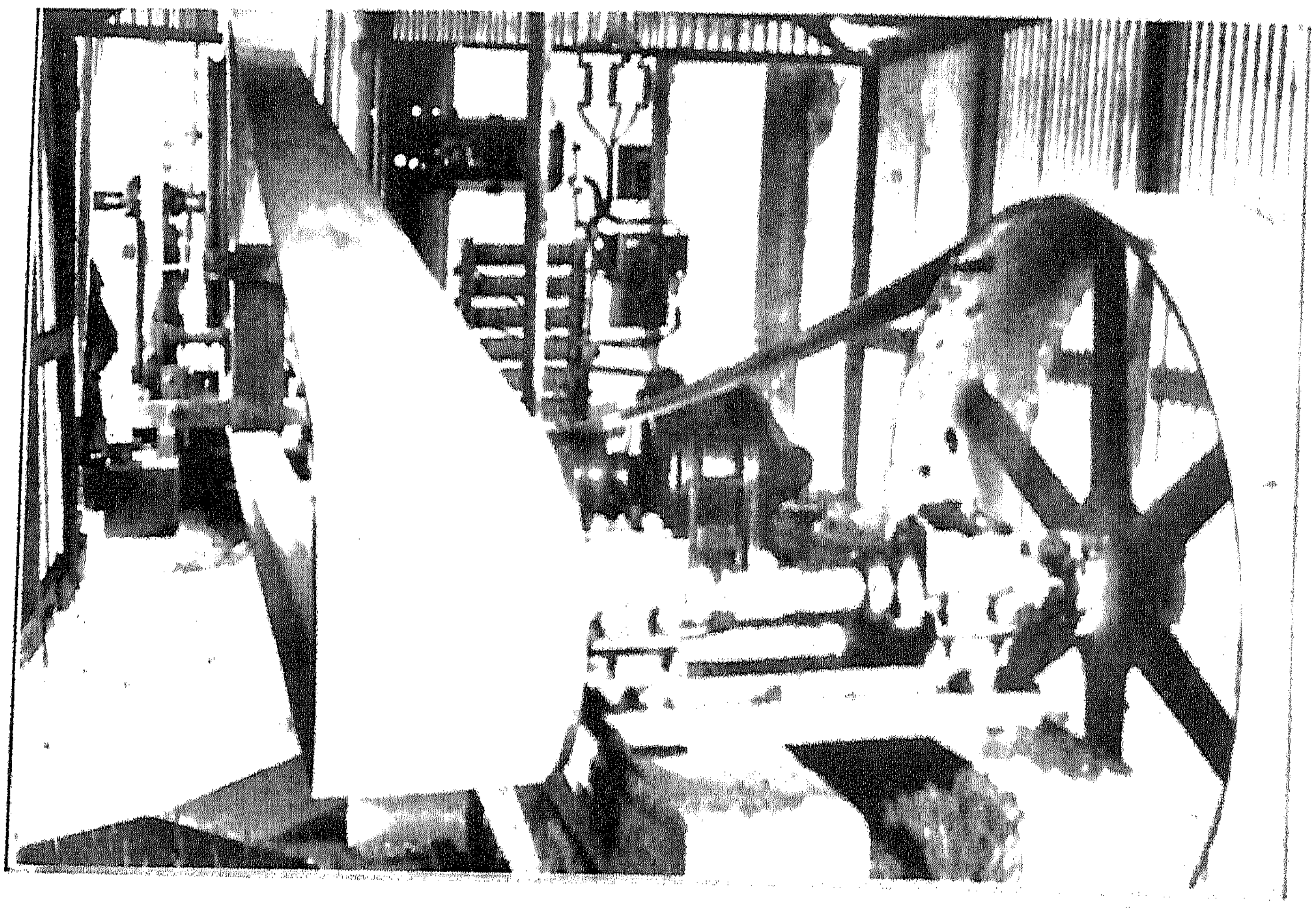

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FIG. 11—TYPICAL INSTALLATION OF A TWO-SPEED BELTED MOTOR FOR PUMPING, PULLING AND CLEANING WORK IN THE MIDWAY FIELD IN CALIFORNIA

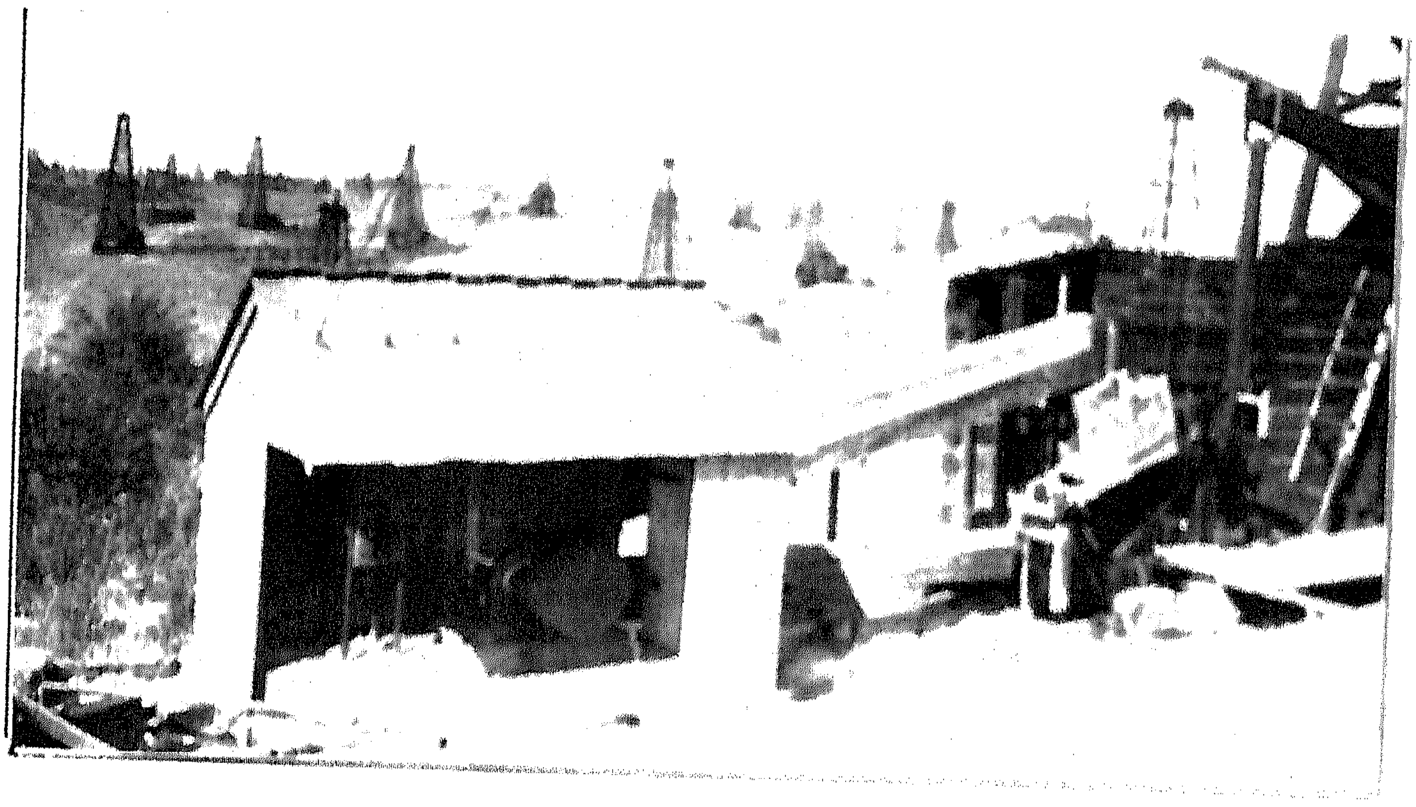

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FIG. 12—BACK-GEARED OIL WELL MOTOR OF THE Y DELTA TYPE IN THE KERN RIVER OIL FIELD IN CALIFORNIA

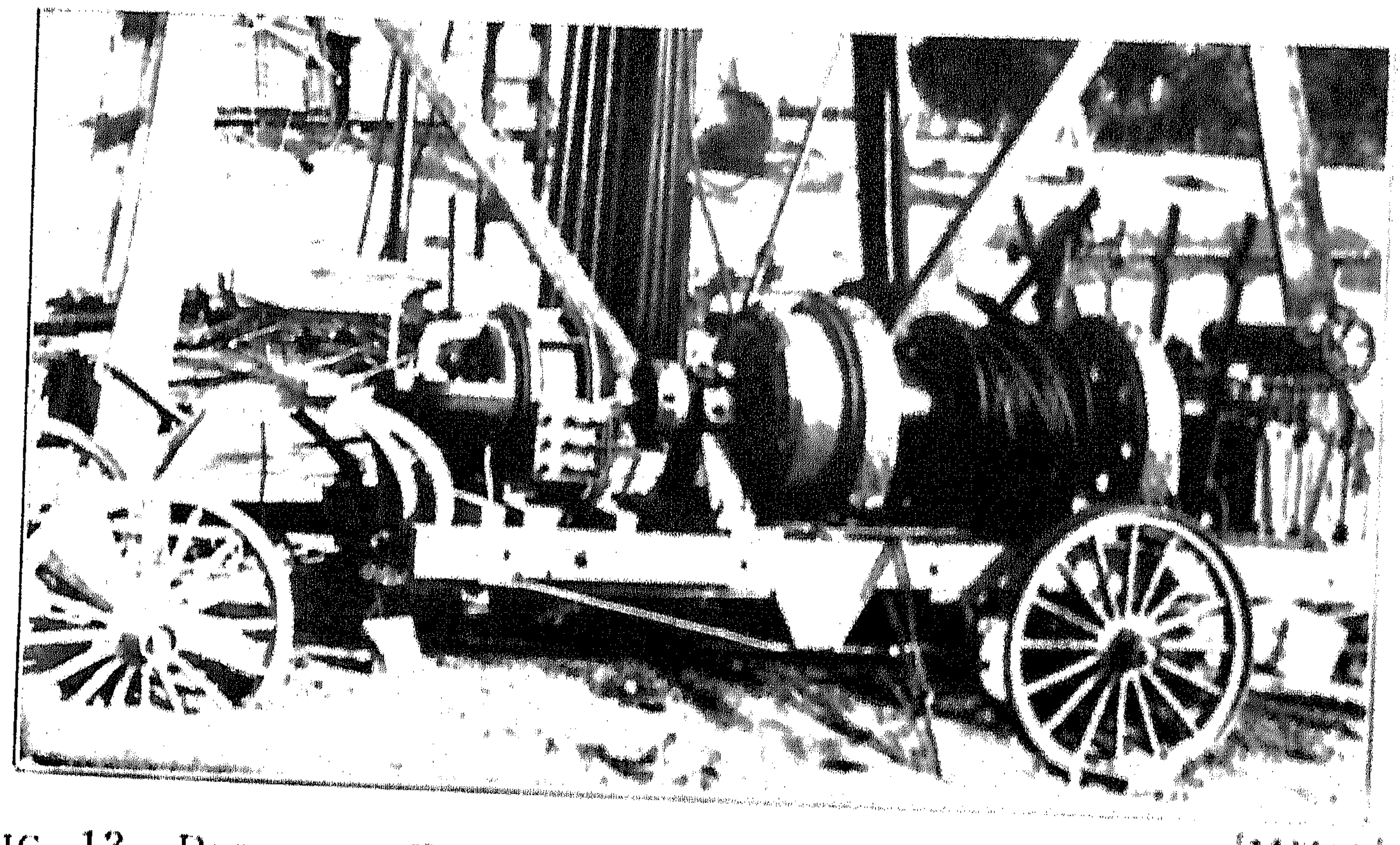

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FIG. 13—PORTABLE ELECTRIC HOIST USED FOR PULLING AND BAILING OIL WELLS PUMPED BY PUMPING JACKS IN THE KERN RIVER OIL FIELD IN' CALIFORNIA

There is no apparent way to calculate the power necessary to pump a well which will give figures uniformly consistent with actual tests, because of the difficulty of determining the effect of varying well conditions. For instance, a large amount of sand in the oil will increase the power necessary to pump it, while on the other hand gas may be present which will help lift the oil. No numerical value can be placed on these conditions, so the motor capacity for this duty is determined largely by comparison with results obtained on other wells. Owing to the fact that the conditions are generally changeable, it is best to have some reserve motor capacity for pumping. The power input will vary from day to day and even from hour to hour, and may increase considerably in a short time when the well is sanding up. Such variations are not so common, however, where the troubles from sand are few.

The following summary of records from over 200 California oil wells pumped on the beam, gives an idea of the motor load for pumping alone:

Depth of wells	900 to 3100 ft., average 1430 ft.
Length of stroke	29 to 32 inches.
Strokes per min	20 to 30, average 24.
Diameter of tubing	3 inches.
Power required	1 to 5 h.p., ave. 3.5 to 4 h.p.

Exceptional wells in California have required as high as 16 to 17 h.p. at times. In Louisiana some heavy pumping wells have been encountered, one in the Evangeline field requiring the following:

Depth of pumping	1100 ft.
Length of stroke	30.5 in.
Strokes per min	40
Diameter of tubing	2.5 in.
Power required	9.5 h.p.

Another Louisiana well near the Caddo field gave test results as follows:

Depth of pumping	1000 ft.
Length of stroke	37.5 in.
Strokes per min	38.
Diameter of tubing	3 in.
Power required	17.5 h.p.

Compared with the California wells, these Louisiana wells have a longer stroke, higher speed, larger percentage of water and less gas in the oil, and therefore require more power. The

Caddo well, compared with the one in the Evangeline field, has a little lower speed, but larger tubing and less gas in the oil, and therefore takes more power. The depth of well does not usually appear to be a factor from which any logical conclusions can be drawn.

It is interesting to note that the counterweight which is now quite widely used on the walking-beam to counterbalance the weight of the rods in the well was originally installed to reduce the motor load fluctuation on each stroke, and was found to effect a saving in power as high as 22 per cent in some instances. Its use has since been extended in many cases to engine-driven rigs.

Where changes are frequently taking place in well conditions such as the rate of oil flow, the amount of sand with it, the amount of gas or water in the oil, the viscosity of the fluid or the condition of the pump itself, it is necessary to have a variable-speed motor to permit the operator to pump at what he considers is the maximum economical rate, which may be limited by the rate of oil flow or the rapidity with which the rods and plunger will drop in the oil on the down stroke. On the other hand there are many cases where squirrel-cage motors meet all the requirements of pumping.

Pulling the rods and tubing is ordinary hoisting work, carried on at a maximum speed of the band-wheel which may be from 50 per cent to 100 per cent higher than the pumping speed. It demands an intermittent motor output of from 35 to 80 h.p. or even higher under some circumstances. A high torque machine is therefore most suitable. The greatest heating of the motor occurs when handling rods, because of the very frequent reversals which may occur from three to five times a minute for an hour and a half to two hours at a time. Low armature inertia is consequently very desirable. Pulling tubing requires the highest torque and determines the size of motor necessary. The rating usually given the motor for this duty is merely nominal, as the maximum torque obtainable is the determining feature. The maximum load is that encountered when lifting together the rods and pump and the tubing full of oil. In determining the motor capacity it is convenient to use the following formula for the horse power required to lift tubing at a uniform rate of speed:

$$\text{h.p.} = \frac{W \times d \times N}{63{,}000 \times L}$$

in which W = weight lifted in lbs.
d = diameter of bull-wheel shaft in inches.
N = rev. per min. of bull-wheel.
L = number of lines used in the tackle.

The constant 63,000 is based on a mechanical efficiency of the rig of 50 per cent. This is a fair assumption for the majority of cases, as will be seen by reference to Fig. 8, which is an approximate efficiency curve plotted from the results of several tests. In addition to the value obtained from this formula there must remain a sufficient margin in torque for acceleration. This depends largely upon the flywheel effect of the motor armature, as the revolving parts of the rig have relatively small inertia.

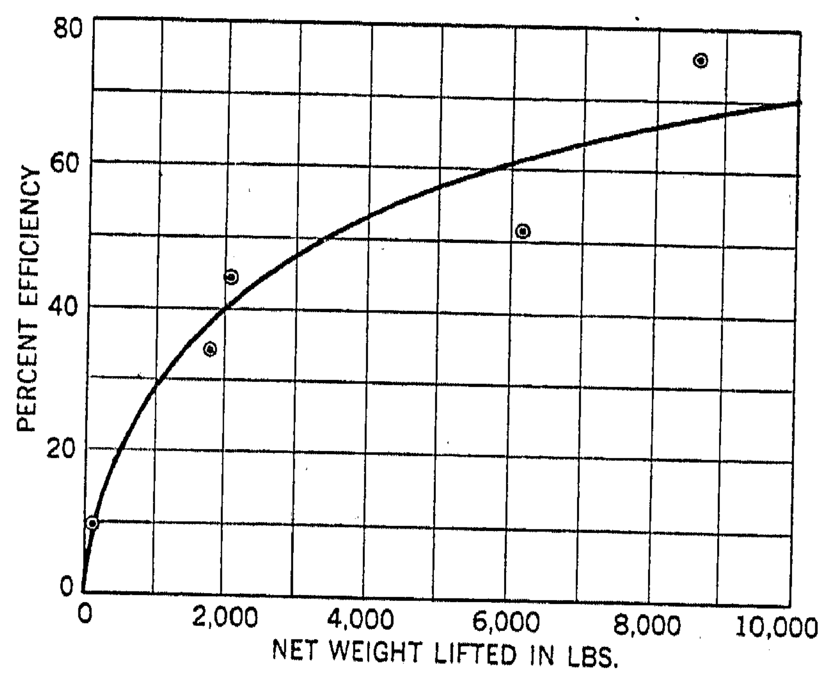


FIG. 8—APPROXIMATE MECHANICAL EFFICIENCY OF STANDARD AMERICAN OIL WELL RIG

Of the various operations of cleaning a well, swabbing requires the heaviest demand of power. The work consists of lowering a plunger into the well casing and then pulling it out. The plunger has a tight fit in the casing so that the suction thus produced draws the sand out of the perforations at the bottom and thus clears the oil passages. The operation may be performed for several hours at the rate of two to four times per hour, each hoisting trip of the swab requiring several minutes. Peak inputs to the motor from 40 to nearly 70 kw. have been recorded in this work.

The total monthly power consumption for all the work of pumping, pulling and cleaning a well will vary from approximately 1350 to 6000 kw-hr. but the average is about 2100 kw- hr.

The necessity of employing a single motor for all of the work of pumping, pulling and cleaning is due chiefly to two reasons; first, the impracticability of using a portable hoisting equipment for wells that may have to be pulled every few days, particularly where the country is rough; second, the desire of a great majority of operators to have a machine which will take the place of the steam engine with little or no change in the method of operation.

The most successful and most widely used induction motors for this duty are of two types, the 'Y-delta' and the two-speed. Except in special instances both are of the slip-ring type, the former being designed for changing the normal capacity by a change in stator connections made by a suitable switch, this not, however, affecting the speed; the latter has a pole-changing switch mounted on the frame by means of which both the speed and capacity are changed. Both machines require a controller and secondary resistance for speed variation, which with the two-speed motor are effective on either the high or the low-speed connection, as a six-phase rotor winding is used. A synchronous speed of 900 or 1200 rev. per min. is usually selected for either type of motor, and a half-speed connection is used on the two-speed machine. Various ratings are employed, depending upon what the conditions require, among which are 20/7 h.p., 20/10 h.p., 25/8 h.p. and 30/15 h.p. Smaller motors than these generally cannot develop the overload torque occasionally necessary in emergencies on nearly all wells. The low capacity is used for little else but pumping, and the design is therefore made for as high an efficiency as possible on this connection without sacrificing the required torque on the higher rating. The maximum momentary capacity is from 300 per cent to 450 per cent of the high rating, but full-load efficiencies of from 75 per cent to 85 per cent, and power factors nearly as good, are nevertheless obtained at full load on pumping duty.

With the Y-delta motor, a high speed for pulling can be obtained only by changing the pulley or by lagging up the bull-wheel shaft to a large diameter. Few operators care to be bothered with the pulleys, while there are some who will not consider the other method because of the increased strain on parts of the rig. Lagging the bull-wheel shaft furthermore does not speed up the sand-reel, so bailing must be done very slowly. But where the operator will use a lagged shaft and has no sand-reel, the Y-delta motor does very well, except for one point which

in many cases is important. It is very often the practise to 'shake-up' a well to free the pump valves from sand and thus avoid pulling the rods and tubing. This is accomplished by increasing the speed of the walking-beam for a few minutes, but there is no practical way to do so with this type of motor, as the time required to change pulleys makes this method out of the question. The two-speed slip-ring motor, as may readily be seen, overcomes all these difficulties and has therefore received wide-spread approval by practical oil men. One of these motors is illustrated in Fig. 9.

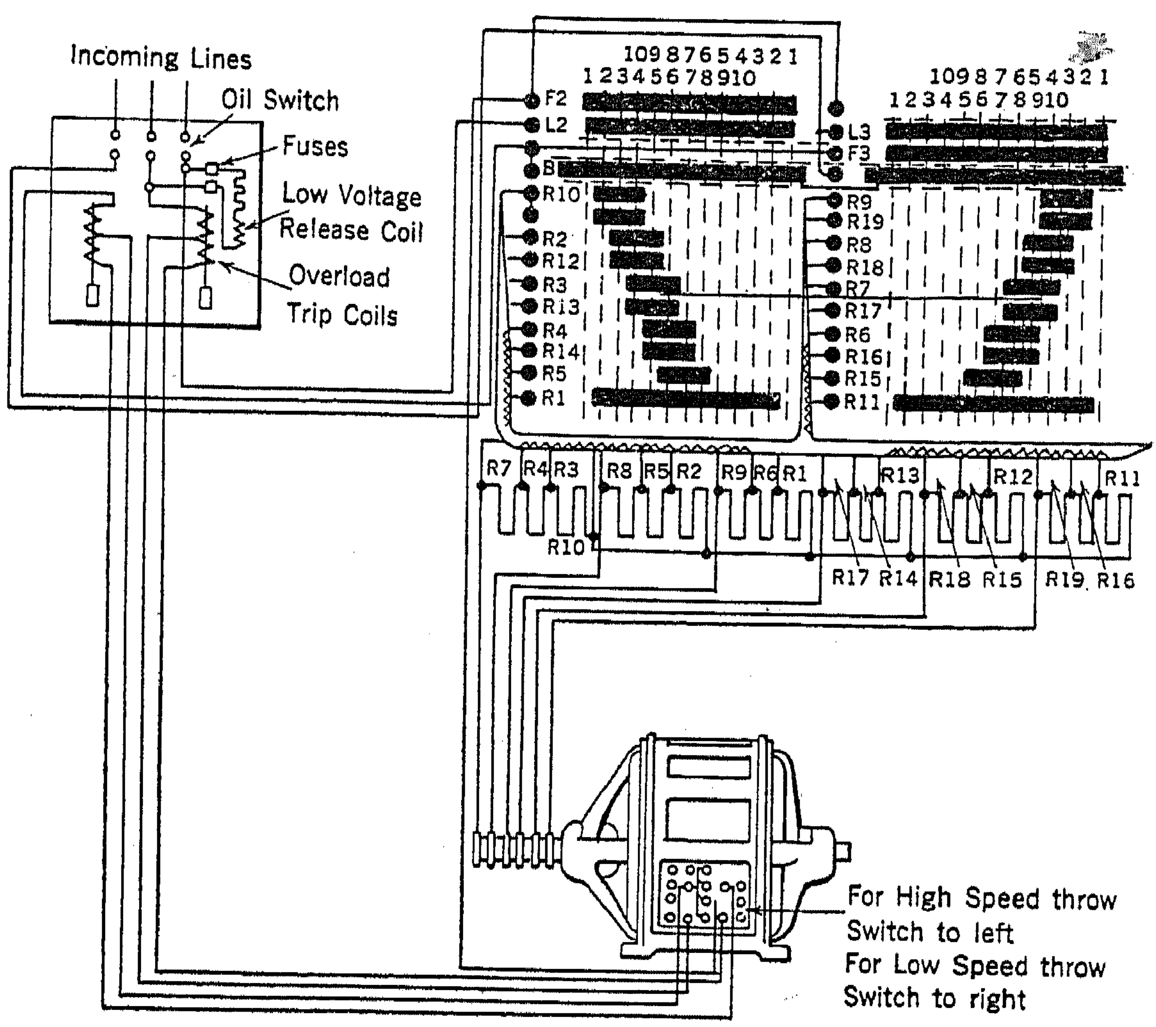


FIG. 10—CONNECTIONS FOR TWO-SPEED MOTOR EQUIPMENT FOR PUMPING, PULLING AND CLEANING DUTY

The connections of the two-speed equipment in Fig. 10 show the method of protecting the double-rated motors by double-wound overload trip coils on the oil switch, which are so interlocked by connections with the switch on the motor that proper protection is automatically obtained. The controller is operated by a rope wheel from the derrick as described for the drilling motor.

While the majority of installations use a belted motor with countershaft, there are many back-geared machines in operation, the two arrangements being shown in Figs. 11 and 12. Oil men display a preference for the former, but most of the gear noise

has been eliminated on the most recent back-geared installation by the use of cloth pinions, and it is anticipated that more of these will be used in the future.

The use of separate motors for pumping and pulling work requires little comment, as it is a simple proposition to select machines with the proper characteristics. The hoist motor must be portable, and either it may be coupled to a hoist mounted on a truck as shown in Fig. 13, or the motor equipment may alone be portable and designed to be belted to the countershaft at each well. Both methods are successfully used. The complete portable hoist is better adapted for wells pumped by pumping-jacks.

Pumping-jacks are operated together from a central point, the reciprocating motion being obtained by eccentrics or cranks which are belt driven. Motors have been applied to a large number, but no features of unusual interest are involved, as the duty is non-reversing and a friction-clutch is frequently used for starting the load. It is an interesting comparison with the individually driven well to note that the power required for jack-rig pumping averages approximately 2.5 h.p. per well and the average consumption is from 30 to 45 kw-hr. per day. The use of jacks has more than cut the power bill in two in some cases, but they are considered advisable only when the well production falls very low, as their use causes a loss of from 15 per cent to 25 per cent in production because of the impossibility of running each well at its most advantageous speed.

Oil well motors have been used in eastern United States fields for the past twelve years, but active interest was not taken in them in California and the middle west until 1910. The conditions encountered in those fields required the development of the equipments described in this paper, which with little or no change can successfully meet any conditions so far encountered in this country. During the first three years over a thousand wells were electrified in California alone. Although very little development work has taken place in the fields during the past two years due to the very low market price of oil, it is estimated that there are between 1500 and 2000 electrically-operated oil wells in the United States at the present time.

No attempt has been made in this paper to give comparative operating costs, as a considerable amount of valuable data on that subject has already been published and is readily available to those interested.

Discussion on "Motor Equipments for the Recovery of Petroleum" (Taylor), Cleveland, Ohio, June 27, 1916.

F. Woodbury: About five or six years ago I was associated in the pioneer work near Los Angeles where some of these oil well motors were developed. We had considerable trouble owing to the prejudice of the operators against the apparatus, as mentioned by Mr. Taylor. They endeavored to discredit the motors by running full speed and reversing as fast as they could, doing everything possible to burn them out. However, in this they were not very successful, and we finally succeeded in successfully installing several motors.

The largest saving to be effected by motor operation is with producing wells which require pumping. Wells in process of drilling are comparatively few, so it is questionable if much is to be gained by using motors for this severe duty. An example of what was saved on the property where the development work took place is herewith given. Before electrification all of the natural gas on the property plus 30 to 50 barrels of oil was burned per day to produce the necessary steam for the pumping engines. After equipping 15 or 20 wells with pumping motors it was found no longer necessary to burn any oil, and there was an excess of natural gas. Electric power was supplied from a small plant receiving steam from the same boilers that were used to supply the pumping motors.

Mr. Taylor notes that there are many instances where it is hard to get motors installed due to local conditions not being suitable. This is quite true in cases where there is ample natural gas and the prospective customer is using gas engines. In other cases where crude oil is used for steam generation and the steam is piped considerable distances, large savings can be made by using motors.

A. M. Dudley: There is one fact that Mr. Taylor has not dwelt on, and that is the greater convenience of the electric motor. In such territories as the oil fields of West Virginia the hauling of a heavy steam boiler over the rough country is a serious problem. Six horses and even eight are often employed. You can readily appreciate that a motor occupying possibly 4 or 5 cubic feet and weighing not over 700 or 800 pounds is a most acceptable substitute.

Another point, is the great flexibility of the induction motor in the performance of any and all classes of work. It has been brought to your attention in connection with the paper on reversing rolling mills that in many cases the limiting factor of the d-c. motor is commutation. The induction motor has no commutation and for short-time loads is limited practically only by the maximum torque it will develop. Mr. Taylor also shows that by connecting Y and Δ, a maximum torque practically three times as great may be developed where needed for short

periods in cleaning and "pulling." and that this is coupled with high efficiency when pumping continuously for days at a stretch. Another point brought out, is the possibility of connecting the same winding for two speeds and thus further adapting the motor to its work. From many points this is almost an ideal combination of motor and tool characteristics.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

REPORT OF THE TRANSMISSION COMMITTEE

I—DATA FROM OPERATING PLANTS ON THE EFFECT OF ALTITUDE ON THE OPERATING TEMPERATURE RISE OF ELECTRICAL APPARATUS

BY PERCY H. THOMAS, CHAIRMAN

RECOGNIZING the absence of conclusive data on the altitude correction to be applied to the temperature rise of electrical apparatus, and further the lack of uniformity of the general practise as well as the frequent entire omission of the correction, the Transmission Committee undertook the collection of data as to the opinion and practise of operating engineers and sent a list of questions to 150 companies and individuals.

The information received is herein summarized and discussed. It should be noted that no effort has been made by the Committee to make laboratory tests or scientific investigations—nor does the Transmission Committee offer any definite rule of correction, for this is the function of the Standards Committee. The data collected are presented as information for the use of any committee or individuals who may find it helpful.

Thirty-one replies were received. Of these 15 were from plants operating apparatus at 5000 ft. (1524 m.) altitude or higher, which are here called high-altitude plants. Of these 15 high altitude plants six make no correction for altitude and six have noticed no effect of altitude. Comments of more or less interest have been received from some of the above and are here summarized.

From W. N. Clark, Arkansas Valley Ry. Lt. and Pr. Co., Canon City, Colorado.

Altitude 9000 to 10,000 ft. (2743 to 3048 m.)

Take account of altitude both in purchasing and loading transformers. Have no definite rule for correction but have by experience determined which design of transformers operate satisfactorily. The transformers in question are step-down transformers in the Cripple Creek district, ranging in capacity from 100 to 900 kw.

We have noted that on some of the more modern closely rated equipment that the temperature remains high. This does not apply to some of the older more liberally rated apparatus such as generators and transformers.

Six 200 kv-a., oil-insulated, self-cooled transformers required water cooling coils to prevent constant excess temperature at rated capacity, however, part of the cause was poor circulation of air in and out of building.

The correction factor is not large. I think it should be made. I think the capacity should be rated lower for the higher altitudes, something similar to the method of rating air compressors.

Lightning discharges take place over longer setting of horn-gap arresters.

From W. O. Vickery, The Trinidad Electric Transmission. Railway and Gas Co., Trinidad, Colo.

Altitude 6000 to 7000 ft. (1828 to 2133 m.)

No account taken of altitude up to spring of 1915.

No rules adopted, but it is thought best in future to specify temperature and altitude in purchasing electrical apparatus.

From general observations it is noted that oil-insulated, self-cooled transformers run approximately 10 per cent higher than manufacturer's guarantee. This is also noted on induction motors, except that induction motors run only about 7 per cent higher than guarantees. Generators seem to operate about 5 to 6 per cent higher than guaranteed rating of temperature.

Nothing definite. However, the loss of the coils in a 2000-kw. turbo-armature we believe could be partly attributed to higher temperature resulting from high altitude.

Generally speaking, increased temperature at high altitudes was called to our attention in the spring of 1915. Since that time, observations have been made, which lead us to believe that there is considerable increase in temperatures of electrical apparatus when operating at altitudes of 7000 to 10,000 ft. (2133 to 3048 m.) above sea level, and it is believed rules should be formulated covering such apparatus when making purchases.

From R. W. Toel, Chf. Engr., Denver Tramway Co., Denver, Colo.

Altitude 5280 ft. (1609 m.)

Take account of altitude in loading transformers.

Air transformers have been noticed to operate from 10 to 12 deg. cent. higher than manufacturers specifications under given load conditions.

Air transformers have failed due to high temperatures, operating under normal conditions.

Should think that a correction factor should be made of at least 10 deg. cent. higher than temperature rating for apparatus used at sea level under same operating conditions.

From J. H. Rider, 8 Queen Anne's Gate, Westminster, S. W. London.

Altitude 6000 ft. (1828 m.), neighborhood of Johannesburg, So. Africa.

Takes account of altitude in generators, motors and transformers both in purchasing and loading apparatus.

To secure a maximum temperature rise of 35 deg. cent. in motors with an ambient air temperature of 35 deg. cent., motors must not exceed a temperature rise of 30 deg. cent. with an ambient air temperature of 25 deg. cent.

The neighborhood of Johannesburg is at an altitude of 6000 feet above sea level, and from experience there I have had to adopt the following basis for the temperature of the motors, namely, a maximum temperature rise of 35 deg. cent. with the surrounding air at a temperature of 35 deg. cent.

As the plant has to be tested at the maker's works at sea level, the prescribed limits for such a test are a temperature rise of 30 deg. cent. with the surrounding air at a temperature of 25 deg. cent. as experience has shown that these figures correspond very closely indeed with the limits for the higher altitudes.

I have had considerable difficulty with some manufacturers in getting them to design their plant for what appears to them to be abnormally low temperature rises at sea level, but by persistence have succeeded now in getting those figures without difficulty.

Yes; correction should be made for altitude.

From K. C. Randall, 133 *Dewey Avenue, Edgewood Park, Pa.*

Have never allowed nor encountered requests for allowance in rating of apparatus because of expected operation at high elevations.

Have never heard of instances where loading is in any way controlled by elevation.

I believe that in general the extra complications from introducing corrections for elevation will be largely a paper burden and in general of no material significance, particularly as standard apparatus should be employed as far as possible and that any acknowledgment of the effect of elevation will only add to the expense of both consumer and manufacturer without any return to either. This is particularly true, as the wide range of conditions of installation, ventilation and operation will have in general much more bearing on operating conditions than variation in elevation.

From Charles S. Ruffner, Genl. Mgr., The Electric Company of Missouri, Webster Grove, Mo.

Confining the questions strictly to the effect of air pressure on thermal conditions. might omit considering other factors in the cooling of apparatus at high altitudes. The prevailing lower temperatures at high altitudes, with particular reference to the invariably cool nights, might, in practise entirely offset any difficulty with the volumetric thermal capacity of the air.

Personally I have not noted any cooling difficulties in any apparatus operated at high altitudes arising from the rare atmospheres, and I cannot think of any important practical question in that connection excepting only in the design of forced ventilating systems. In that case, the

apparatus being cooled by air blast might require a larger v air. Such a case has not, however, come under my observat

A few simple experiments on the rate of transfer of he substance to atmosphere of different pressure might determine of air at different pressures required for equivalent cooling e:

From P. M. Downing, Chf. Engr., Hydroelectric De Gas and Elec. Co., San Francisco, Cal.

In this connection I might say that the effect of altitude on ature reading of electrical apparatus, is something that we considered of great importance. The writer has had persona in the operation of such apparatus at altitudes ranging from 8500 ft. (2590 m.), and although I have never made any c have never been able by casual observation to notice any ch heating of the apparatus.

From C. D. Gray, Asst. Elec. Engr., J. G. White E Corporation, 43 Exchange Place, New York.

Our personal opinion is that if the altitude is over 6000 (1828 or 2438 m.) some attention should be given to this mat would probably specify about 5 deg. lower temperature than fo: used at lower altitudes.

From J. F. Dostal, Genl. Mgr., The Colorado Sprin Heat and Power Co.

Altitude 6000 and 7000 ft. (1828 and 2133 m.)

Take no account of altitude either in purchasing o apparatus.

Feel that some allowance should be made. Have noticed run hot.

From E. R. Davis, Genl. Mgr., Pacific Light and Po poration, Los Angeles, Cal.

Altitude 5000 ft. (1524 m.)

To yours of July 26th covering data sheet for references tc altitude in temperature of electrical apparatus, the replies to all tions except the first may be summed up in the statement company is not taking any account of the effect of altitude on apparatus and has no observations or tests on record which w any bearing on the matter.

The above data indicate clearly that most engineers o at altitudes over 5000 ft. (1524 m.) have ignored the of the effect of altitude on the operating temperature of e apparatus. This appears rather to be because of lack on their own apparatus and lack of convincing engineeri in any form. As at most, the effect of altitude involves a tion of only a few per cent and as apparatus is seldom to exactly 100 per cent of capacity, the point of view is r However, at the higher altitudes where engineers have m

effort to look into the subject they usually conclude that a correction should be made.

While in most cases the altitude correction is not important, there are some where it is of great importance, for example to such a company as the Chile Exploration Company which expects to have 100,000 kw. of transformers and motors at 9000 ft. (2743 m.) altitude, much of which will be carefully rated, or as the Cerro de Pasco Mining Co. with apparatus at the extreme altitude of 14,000 ft. (4267 m.)

Obviously the data collected by the committee form no basis for the drawing of a definite altitude correction, and the collection of data was not undertaken with that in view. It serves however to show the attitude of engineers in general on this question and thus it is of considerable interest.

Two of the replies above quoted are to the effect that their authors considered that the altitude correction is not of magnitude enough or sufficiently precise to warrant a formal rule.

Two of the replies included certain matters not strictly pertinent to the subject of the inquiry but still cognate and of some interest, they are appended below.

From J. H. Rider, 8 *Queen Anne's Gate, Westminster, S. W., London.*

One of the things which no manufacturer ever pays attention to is that the temperature rises of generators and motors tend to increase as time goes on, even with the same load. This is because the first temperature tests are made with the machine in a new and clean condition, with all ventilating passages in good order. During working, however, it is impossible to keep dirt from collecting in the air passages, and so the ventilating facilities get worse and worse, as time goes on.

It is quite impracticable to clean out the ventilating spaces without dismantling and then rebuilding the whole machine, which, in practise, is impossible, as a user is entitled to expect his machine to run satisfactorily for very many years, if he gives proper attention to the bearings, brushes, etc.

The above point, perhaps, does not concern only motors which are intended to work at high altitudes, but it shows that the test temperature of such machines at sea level must be quite as low as those which are fixed upon if satisfactory after-running is to be obtained.

If your committee, therefore, could both fix upon a standard for temperature tests at sea level to give reasonable working temperatures at high altitudes, and also make such sea level figures low enough to provide for the gradual clogging of the air passages, you will have done a very great work.

From R. S. Masson, 705 *Security Building, Los Angeles, Cal.*

I was much interested in your letter about the effect of altitude on the temperature rise of electrical apparatus. I have been determining for

a number of years in my own mind that humidity was the real nigger in this altitude woodpile. In other words, I am of the opinion that altitude as such does not effect the cooling capacity of the air to any material extent, but that humidity, which may be directly related to altitude in some instances, causes the trouble.

When the writer undertook to operate certain motor-generator sets in Phoenix, Arizona, about three weeks ago, it was found that the machines ran very much above their testing temperature and, after accusing power factor and other common enemies, it was found that there must be another cause. Phoenix was then a close neighbor to great areas of desert and the average humidity was so low that the air was practically dry. We then tackled this problem of constructing a humidor which, in effect, was not much different from any of the attempts which have been made by power house operators; ours having the form of water screens rising out of a water bath like the old overshot water wheel with the air flowing through these screens. This air was conducted through canvas housings to the ends of the motor generator sets and allowed to flow out through the stators, without changing the machines themselves at all. The effect was very marked and increased the capacity of the normal rated 600-kw. machines about 125 to 150 kw. at the same temperature rise.

Referring then to the problem as presented in your letter. Here was a machine located at an elevation of about 800 ft. (243 m.) which was having all of the troubles that had previously been experienced at altitudes of 8000 and 10,000 ft. (2438 to 3048 m.) It would be interesting to have some of the operators of plants in high altitudes test out this method of cooling the air to see if they cannot put their machines on the same basis as the sea level machines.

This test which we made, however, was not quite true, as the effect of blowing the air through these water screens was to actually cool the air by evaporating the water and, of course, the machine was practically running in a lower temperature. In order to make a true test of the effect of humidity alone it would be necessary to re-heat the air, after it has accumulated moisture, to the temperature of ordinary air. This test I will be glad to make, if it would be of any interest, as it can be done in the said Phoenix motor-generator apparatus without inconvenience or unnecessary delay.

The above extracts are self explanatory.

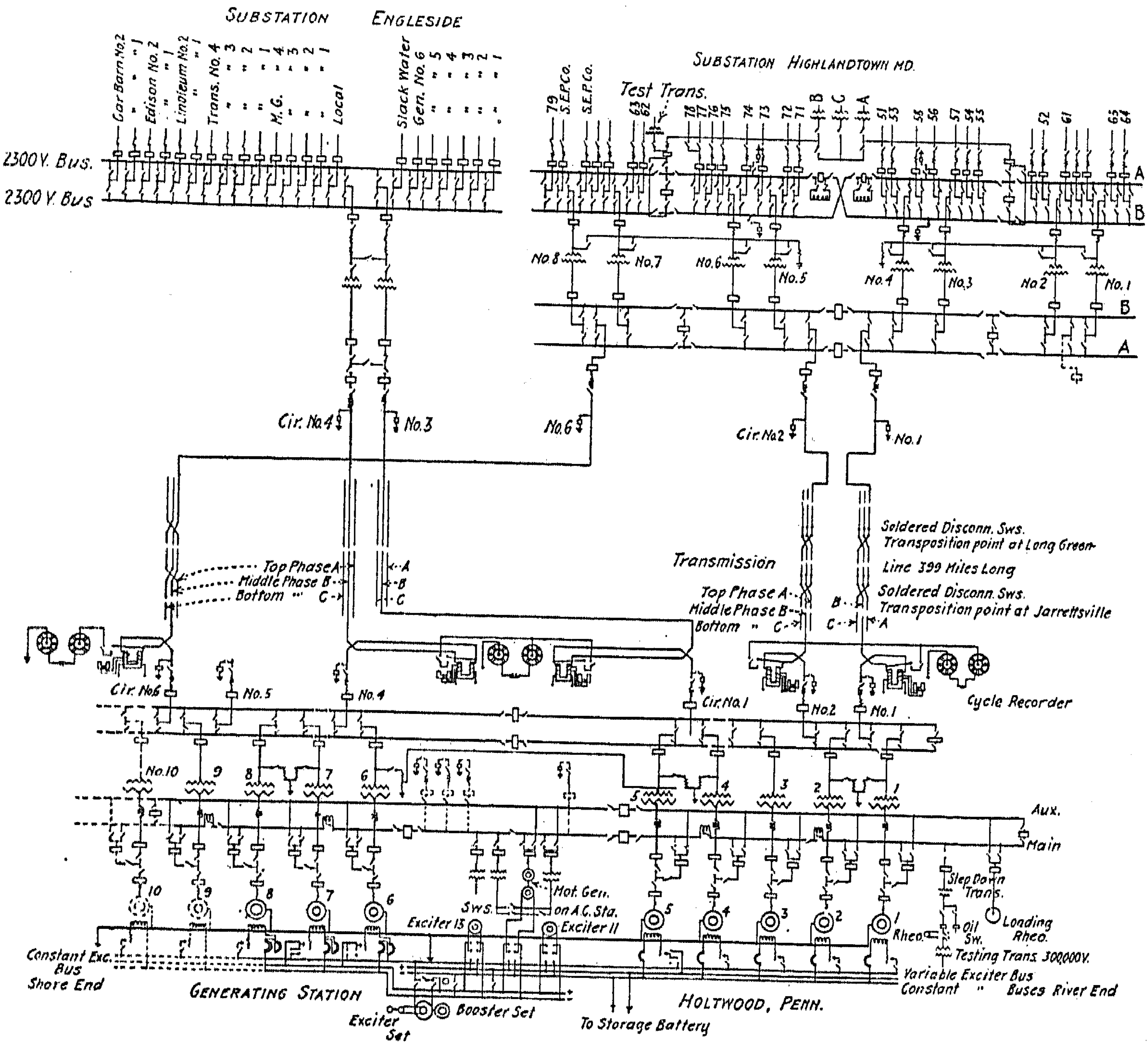
II—EXPERIENCE WITH GROUNDED NEUTRAL ON HIGH-TENSION TRANSMISSION LINES

To secure a comparison of the experiences of various companies operating high-tension systems with grounded neutrals, the Transmission Committee sent an information blank to a large number of power companies and the present report covers the information secured.

It is believed that the various replies can be best offered by printing verbatim or in rearranged form the more important reports; comments will then be made.

From the Pennsylvania Water and Power Company, Mr. A. Bang, Testing Engineer.

The Pennsylvania Water and Power Company operates a hydroelectric plant located at Holtwood, Pa. The generating capacity of this plant is at present about 83,500 kw.; the current is three-phase, 25 cycles, and generated at 11,000 volts. This voltage is stepped up to 70,000 volts by means of three-phase transformers, which are delta connected on the low-tension side and star connected on the high-tension side.



ONE-LINE WIRING DIAGRAM OF GENERATING STATION—TRANSMISSION AND SUBSTATIONS

The bulk of this power is transmitted to Baltimore, Maryland, through three 70,000-volt 40-mile (64-km.) long transmission circuits. At the terminal station in Baltimore the voltage is stepped down from 60,000 volts to 13,200 volts by means of three-phase transformers, delta connected on the high-tension side and star connected on the low-tension side. This power is then distributed through a 13,000-volt underground cable system to a number of substations located in Baltimore.

A minor part of the power generated at Holtwood is transmitted at 70,000 volts to Lancaster, Pa., where the voltage is stepped down to 2300 volts through single-phase transformers connected in open delta.

The accompanying one-line wiring diagram and tabulations of the resistances and reactances of the various apparatus used in the generation and transmission of power will give an idea of the size and characteristics of the plant and transmission system.*

The transmission of power to Baltimore was started in the autumn of 1910 and to Lancaster in the autumn of 1913.

Both of these systems are run with the neutral grounded at the power house only. The Lancaster system has always been run grounded; the Baltimore system has been grounded all the time except for a short interval during the summer of 1911 when the grounds were temporarily disconnected to try out such method of operation.

Ungrounded connections did not seem to give any relief from lightning disturbances experienced during that summer and it was felt that when run ungrounded the possibility of the line being kept in service for any length of time, with one phase accidentally grounded and without the location and the character of the ground being known, there would be incurred danger to life and property along the transmission line and especially would nearby telephone service be exposed to damage. As in the case of *short circuits* on the transmission line, a very brief interval of arcing may suffice to cause great damage to conductors and insulators on account of the large generating capacity back of the trouble, and as the majority of the transmission-line trouble has been short circuits and not single grounds, it has been thought better not to make any difference between these two cases, but to try to cut out the circuit immediately upon its becoming faulty and carry the voltage on a duplicate circuit, independent of whether the cause of the trouble was a short circuit or a single-phase ground. It has been endeavored to arrange the relay apparatus so as to cut down as far as possible the number of seconds that a faulty line may be exposed to short circuits.

The Baltimore system, where there are three transmission lines, is normally operated so that certain groups of transformers are connected to each line in such a way that the high-voltage sides of the lines are entirely independent, while the low-tension sides of the transformers are all connected to the same bus; though to some extent separated by reactance coils.

For this system two transformers per circuit are grounded during the lightning season, whenever possible. The object of this arrangement is to obtain a heavier rush of current on that transmission line on which the spill-over occurs so as to operate special series relays used in connection with the Nicholson arc extinguisher which is installed on these lines. Tests indicate that there is no harmful interchange of current when the neutrals of two transformers in parallel are grounded, even when these transformers are of different capacity or made by different manufacturers.

*For further descriptive details of this plant and particularly the transmission lines see: (1) Engineering Data Relating to High-Tension Transmission Systems, Sub-committee Report. A. I. E. E. TRANS., Vol. XXXIII, 1914, p. 1013. (2) Foundations for Transmission-Line Towers and Erection of Towers, by J. A. Walls, A. I. E. E. TRANS., Vol. XXXIV, 1915, p. 1201. (3) Four Year's Operating Experience on a High-Tension Transmission Line by A. Bang, A. I. E. E. TRANS., Vol. XXXIV, 1915, p. 1243.

Outside of the lightning season only one transformer per circuit is grounded as a matter of switching convenience.

On the Lancaster system only one transformer is normally used and consequently only one grounded.

At present the transformers are grounded through metallic resistances. The system was originally run dead grounded from the neutral point of one transformer per circuit. It was thought that the ground short-circuit currents produced thereby were too heavy, and that some of the early transformer breakdowns might have been due to this cause, so a resistance was inserted between transformer and neutral ground. From tests and calculations made later it would appear that even with the present reactance coils the current that one single dead grounded transformer can receive may be dangerous, but that this would not be the case if several transformers of the same bank were grounded at the same time and that with all the transformers grounded at the same time, it would be quite possible to run safely without ground resistance. However, this latter arrangement has not yet been tried out as a practical operating condition on the high-tension transmission lines.

On the 13,000-volt cable system in Baltimore the arrangement of having all the transformers dead grounded has been adopted and been in service for the last year and a half apparently without causing any inconvenience. The reason why this system was adopted here instead of the former system where only one transformer was grounded through a resistance was to make certain of a sufficient current on a ground to trip the relays, which on account of the desire to get selective action of the relays between various substations, are set for rather high tripping current. The condition of running entirely ungrounded on the cable system has never been tried but would hardly be of any great benefit, as most of the cable troubles apparently start between conductors, and not as grounds.

The first resistance tried for the transformers at the power house were concrete blocks, which proved unreliable on account of lack of constancy in resistance and because they gave rise to arcing when voltage was built up on them.

Cast-iron grid resistances were then substituted and have been satisfactory on the whole. The difficulties experienced with them are their limited heat capacity in the case of some ground hanging on unexpectedly long, and also on account of the occasional failure of the insulation between grids.

The ground connections used at the Holtwood power house are of different types. In the main they consist of:

(a) Several copper plates buried in the mud in the forebay.

(b) Twenty-four 1½-in. (38-mm.) galvanized iron pipes driven 9 ft. (2.7 m.) in the wet earth in the neighborhood of the first tower of the transmission line.

(c) Several heavy castings lowered in the tail race (the connections to some of these latter were accidentally torn loose and have not been restored.)

(d) Besides the above artificial grounds an effort has been made to tie in all metal parts in the power house with the ground system and to tie in specially with such metal parts as are in direct connection with the river water, as for example, head gates and racks. The power house

grounds are furthermore tied in with the overhead ground wires on the transmission lines. All these connections are made solid and, therefore, do not easily lend themselves to regular tests; such tests are consequently not made, but occasionally inspections are made of the cables connecting with the ground plates, etc., to see that such connections have not been torn loose.

From time to time other tests have been made on the individual "ground" and some of the results are as follows:

(1) Forebay ground consisting of four interconnected copper plates, 2 ft. 6 in. (82.2 cm.) by 3/32 in. (2.38 mm.), buried in the mud, 0.04 ohms.

(2) Large castings in the tail race (three in multiple) 4.4 ohms.

(3) Individual tower grounds on the transmission line, stubs set in concrete but grounded by means of a paragon cone and measurements taken with the ground wire removed, 150 to 350 ohms.

(4) Recent measurements taken between all the power house grounds connected in multiple, and a similar system of grounds at the substation 40 miles (64.3 km.) away, showed a combined resistance of about 2 ohms, though it is not possible to say how much of this is located at the power house and how much at the substation.

The current in the neutral is used to secure selective relay operation in the following way:

One or two of the transformers of each group supplying a transmission circuit have their neutrals grounded at the power house. The ground current from any transmission circuit will, therefore, pass through the neutral ground resistance of that circuit, and this ground current acts through a current transformer on a relay, which latter opens the low-tension switches of the transformers connected at the power house to that particular transmission circuit. This system, from the very start of the plant, has given satisfaction in respect to selective action on grounds and is considered as one of the main advantages of running the system with a grounded neutral. It is to be noted that the above relay action is quite distinct from the action obtained with the Nicholson arc extinguisher, the latter requiring a heavy ground current to energize its series relay, while the former does not require heavy current for the operation of its relay.

The current obtained when an accidental ground takes place on the line will naturally vary greatly, depending upon

(a) The character of the ground, *i. e.*, whether it in itself contains appreciable ohmic resistance or not; but even if we consider that we are dealing only with "dead grounds" the amount of current will vary with the total amount of impedance in the circuit and will, therefore, depend on

(b) The amount of resistance contained in the grid iron rheostat used in the neutral of the transformer;

(c) The number of transformers grounded;

(d) The generator capacity behind the ground;

(e) The location of the ground, *i. e.*, whether near the substation or power house;

(f) Furthermore the ground current will vary with time, being greater during the first few cycles and then gradually dying out, due to the de-

magnetizing of the generators and the heating of resistance grids, in the neutral.

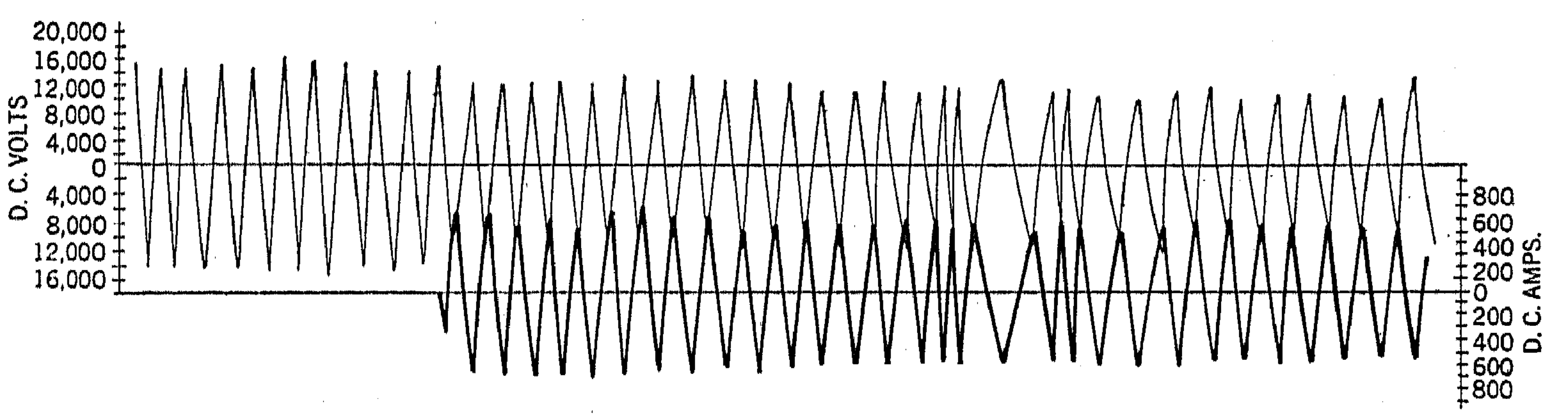
In the following tabulation some results are given of calculations of the ground current as based on a number of oscillograms taken on the P. W. & P. Co's. system to determine the exact value of ground currents for different locations and conditions.

INITIAL RUSH OF CURRENT WHICH TAKES PLACE ON THE P. W. & P. CO'S. SYSTEM WHEN A LINE IS GROUNDED.

BALTIMORE—HOLTWOOD CIRCUIT

Number of generators used	Number of transformers grounded	Location of ground	Initial ground current	Ohmic res. in neutral rheo. per transformer
3	2	At power house	656 amp.	58.4ohms
		At sub-station	430 "	58.4 "
3	1	At power-house	380 "	58.4 "
		At sub-station	290 "	58.4 "
HOLTWOOD—LANCASTER LINE				
1	1	At power house	280 amp.	116 ohms

The accompanying sample oscillogram illustrates the characteristics of such a ground current.



"B" PHASE GROUND IN PINEY ISLAND—GEN. 1 AND 2—TRANS. 1 AND 2 —GROUND STACKS 1 AND 2—VOLTAGE 10,500 VOLTS BEFORE TEST

The operating record for 1915 of the P. W. & P. Co's. system is given below, as far as single grounds are concerned without accompanying short circuits. It should be noted that in *all* cases the grounds were cleared without serious interference with the operation of the system and that none of them lasted more than four seconds. (Only in one case was a small part of the load lost and then only for a few minutes.)

NUMBER OF SINGLE-WIRE GROUNDS ON THE HOLTWOOD-BALTIMORE CIRCUITS, 1915, THEIR CAUSES AND THE METHODS BY WHICH THEY WERE CLEARED.

	Cleared of itself without relay action	Cleared by arc extinguisher	Cleared by interlocking relay	Cleared by hand	Total
Lightning	1	4	1	0	6
Sleet	0	0	0	0	0
Birds	..	..	6	..	6
Insulator failure	0	0	0	0	0
Total	1	4	7	0	12

Grounded operation is preferred as enabling a faulty line to be cut out of service promptly so as to minimize damage to equipment or damage to property or life of outsiders, specially since a short period of operation ungrounded did not prove of benefit in reducing disturbances from lightning spillovers. An advantage claimed for an ungrounded system is that it permits service to be continued in the event of failure of insulators on one conductor, but it is rare to have a sufficient number of suspension units of one insulator string on a steel tower line damaged simultaneously to an extent to cause a permanent ground at that insulator, so that, as far as the circuits of the Pennsylvania Water and Power Company go, the advantage above claimed is of slight importance. The grounding of the neutrals should under certain conditions, result in subjecting the insulation of the high-tension circuit to a stress lower than that obtaining when running ungrounded. However, since the effort has been made on this company's lines to insulate rather against lightning than against generator voltage (insulation for 110,000 volts working pressure being in use on a circuit having a working voltage of but 70,000 volts) such lower stressing of the insulators has not been considered a factor of importance.

In short, grounded neutral operation facilitates certain protective relay operation, while the benefits to be derived from ungrounded operation in the sense of obtaining freedom from trouble from momentary flashovers on a transmission line, or being able to operate for a length of time with one conductor grounded, have not appeared worth while in practise.

The grounding of the neutral at the power house only, does not seem to influence telephone operation at all during normal operation. Whenever a ground occurs on the transmission line and the current therefore is flowing back through the soil to the station, very serious interference with telephone conversations will be observed, but this condition will as mentioned ordinarily not last for more than a few seconds.

Outside the lightning season, both high-tension grounds and short-circuits are cleared by overload relays and ground relays at the power house, and reverse-current relays at the substation. During the lightning season the Nicholson arc extinguisher equipment is put in service and given the first chance to extinguish flashovers on the line. In case this apparatus and the relay arrangement described both fail to clear the trouble, the field is destroyed automatically on all the generators at the power house and brought back again after 1.5 seconds.

As to the chief causes of interruptions, an idea will be had from the tabulation below, which gives a record for the year 1915 of all the disturbances on the Pennsylvania Water and Power Company's system as far as they had their origin on one of the three Baltimore circuits. This record includes both grounds and short circuits. The disturbances are divided into three groups, depending on the momentary loss of load resulting from them, *i. e.*, total interruption (T. I.), partial interruption (P. I.), and mere voltage or frequency disturbances (V. D.).

Operating record for the Holtwood-Baltimore transmission line:

Cause	T. I.	P. I.	V. D.	Total
Lightning	3	13	8	24
Defective insulators	..	1	..	1
Sleet on cables	..	..	2	2
Birds on line	..	..	8	8
Wires blown together	..	1	..	1
Defective cable clamp	1	..	..	1
Lineman's mistake	..	1	..	1

Only a current less than one ampere flows normally in the neutral connection. The frequency of this current is not known.

AVERAGE REACTANCE AND RESISTANCE OF BUS REACTANCE COILS USED IN SHORT-CIRCUIT CALCULATIONS

HOLTWOOD BUS REACTANCE COILS

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 bus reactance coil	21.5 ohm	0.35 ohm	1.037 ohm	0.017 ohm

HIGHLANDTOWN BUS REACTANCE COILS.

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 bus reactance coil	30.8 ohm	0.381 ohm	1.49 ohm	0.0184 ohm

HOLTWOOD-BALTIMORE—TRANSMISSION LINES

	70,000-volt values		13,200-volt values	
	Reactance	Resistance	Reactance	Resistance
1 transmission line	13.1 ohm	12.1 ohm	0.6330 ohm	0.5850 ohm

INDIVIDUAL REACTANCE AND RESISTANCE OF TRANSFORMERS

HOLTWOOD TRANSFORMERS

Operating No.	Office number	Serial number	Kw. rating	Per cent impedance	Per cent reactance	Per cent resistance (at 50°C)	Reactance in ohms — phase H. T. (at 25 cycl.)	Resistance in ohms — phase H. T. (at 50° C.)
1	102.	598555.	7,500	4.03	3.82	1.25	25.0	8.20
2	103.	598554.	7,500	5.14	5.00	1.20	32.7	7.83
3	108.	298572.	10,000	4.98	4.90	0.99	24.0	4.85
4	109.	301699.	10,000	4.98	4.90	0.99	24.0	4.85
5	107.	278098.	10,000	4.98	4.90	0.99	24.0	**4.85**
6	105.	750832.	10,000	4.90	4.84	0.84	23.7	4.12
7	106.	750833.	10,000	3.57	3.52	0.72	17.3	3.52
8	110.	343227.	10,000	4.98	4.90	0.99	24.0	4.85
9	111.	1198081	12,500	5.08	5.03	0.77	19.9	3.02
10	.....	....	....	....	....	....	....	......
				HIGHLANDTOWN SUBSTATION TRANSFORMERS.				
2	207.	360644.	12,500	5.32	5.23	0.95	15.1	2.74
3	201.	237663.	10,000	4.94	4.79	1.21	17.2	4.33
4	202.	237664.	10,000	4.94	4.79	1.21	17.2	4.33
5	203.	237662.	10,000	4.94	4.79	1.21	17.2	4.33
6	204.	237661.	10,000	4.94	4.79	1.21	17.2	4.33
7	205.	278093.	10,000	5.05	4.90	1.22	17.6	4.41
8	206.	324822.	10,000	5.05	4.90	1.22	17.6	4.41

REACTANCE AND RESISTANCE OF GENERATORS AND REACTANCE COILS AT HOLTWOOD

HOLTWOOD GENERATORS

Number	Kw.-rating	Reactance (at 25 cycles) Starting value L. T.	Starting value H. T.	Final value L. T.	Final value H. T.	Resistance at (50°C.) L. T.	Resistance H. T.	Field current amps.	Averages H.T. reactance Start	H.T. reactance Final	H.T. resistance
1	10,000	1.32 Ω	53.4 Ω	5.67 Ω	229 Ω	.0651 Ω	2.63 Ω	275			
2	10,000	1.32 “	53.4 “	5.67 “	229 “	.0651 “	2.63 “	275			
3	7,500	1.21 “	48.9 “	5.67 “	229 “	.1075 “	4.35 “	275			
4	10,000	0.84 “	33.9 “	4.53 “	183 “	.0649 “	2.62 “	275			
5	10,000	0.84 “	33.9 “	4.53 “	183 “	.0649 “	2.62 “	275			
6	12,000	1.48 “	59.8 “	4.78 “	193 “	.0651 “	2.63 “	300			
7	12,000	1.48 “	59.8 “	4.78 “	193 “	.0585 “	2.36 “	300			
8	12,000	1.29 “	52.3 “	5.60 “	227 “	.0675 “	2.72 “	450	49.4	208	2.82

HOLTWOOD REACTANCE COILS

	L.T. ohms	H.T. ohms	L.T. ohms	H.T ohms		
1	0.670 Ω	27.1 Ω	0.01479 Ω	0 598 Ω		
2	0.520 “	21.0 “	0.01082 “	0 437 “		
3	0.520 “	21.0 “	0.01082 “	0 437 “		
4	0.520 “	21.0 “	0.01082 “	0.437 “		
5	0.525 “	21.2 “	0 01432 “	0 579 “		
6	0 580 “	23.5 “	0.01582 “	0.640 “		
7	0.833 “	33.7 “	0.01495 “	0 604 “		
8	0.580 “	23.5 “	0.01495 “	0 604 “		
9	0.465 “	18.8 “	0.01405 “	0 570 “	23.4	0 545

From Public Service Electric Company,
Mr. N. A. Carle, Chief Engineer.

We distribute current at 13,200 volts, three-phase, 60 cycles, with the neutral not grounded. Several years ago, we contemplated grounding the neutral but decided at that time to install an arcing ground suppressor on the system. Since the arcing ground suppressor has been installed we have found that whenever a ground occurred, the surge suppressor would immediately make a dead ground on the phase that was in trouble and this would give the operator time to parallel another line or cable to take the bad one out of service.

The surge suppressor has never failed to operate in case the system became grounded on any one phase, and has, in several instances, in addition to protecting the system, saved employees from becoming electrocuted when they came in contact with the 13,200-volt wires.

We have found in many instances, that a line insulator may arc over, causing an instantaneous ground which is instantly stopped by the arcing ground suppressor cutting in. After taking out the suppressor and testing the line, we found in these cases that the ground had disappeared.

If a ground occurs on a 13,200-volt line paralleling a neighboring telephone wire, it causes a very slight disturbance, the extent of which depends upon the length of the paralleling circuits; the amount of current flowing, etc. In case a short circuit and ground occurs at the same time, the ground suppressor going in would cause very serious telephone disturbances, depending upon the length of the paralleling circuits. In order to remedy any trouble that might arise from this source, we installed in the operating station in which the ground suppressor is installed, instantaneous circuit-opening relays on each generator, so that in case a short circuit occurs on any feeder, the arcing ground suppressor cannot operate.

In my opinion it does not pay to ground the neutral of a transmission system unless the voltage is moderately high, say for aerial systems above 60,000 volts, and for cable systems, above 22,000 volts. It is not so very difficult to insulate cables for 22,000 volts, and it is not particularly hard to get line insulation that will stand up satisfactorily under 60,000 volts. The highest voltage under which we are operating at the present time is 13,200 volts.

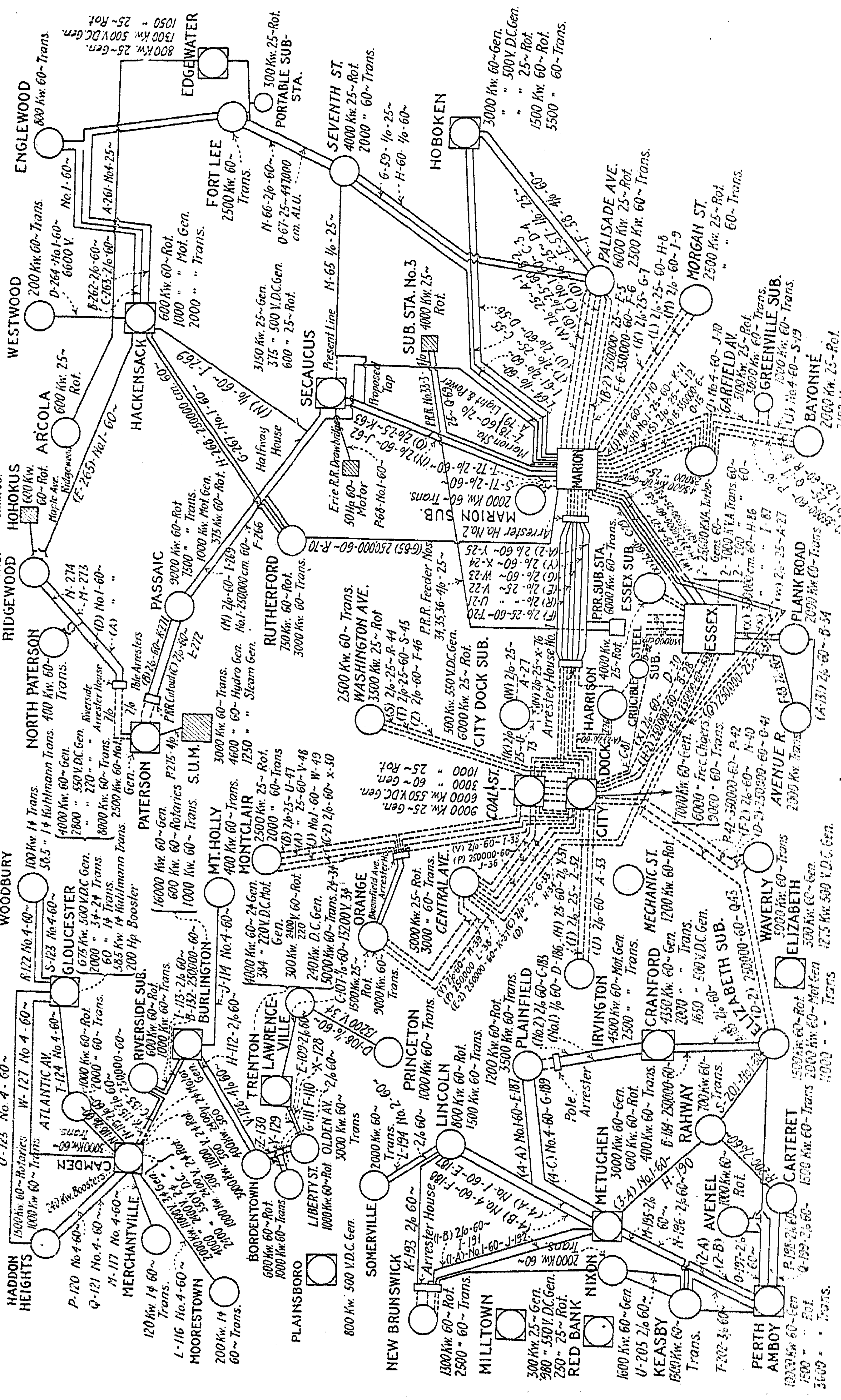
We have had no experience in grounding the neutral but it would seem to me that the proper place to ground it is in the generating station, and that resistances should be used so as to limit the current to an amount great enough to insure the operation of the relays in case of trouble

Our 13,200-volt transmission system in this state is shown herewith.

The surge suppressor is installed in our Marion Station, which is our largest generating station. We also have surge suppressors installed in our Perth Amboy and Burlington stations.

The charging current for the feeders connected to our Marion station, which takes in what is known as the Northern Division, is approximately 75 amperes.

We have five per cent 13,200-volt feeder reactors installed on all 60-cycle feeders from Marion and Essex stations, with the exception that the tie feeders between our City Dock and Marion stations, and between



TRANSMISSION SYSTEM OF PUBLIC SERVICE ELECTRIC COMPANY WITH PEAK LOADS FOR WINTER OF 1914-1915.

our Essex and Marion stations, have 2.5 per cent feeder reactances at each end, making a total of 5 per cent between the generating stations.

Between our City Dock and Marion stations, we have seven three-conductor 13,200-volt tie feeders. At each end of these feeders we have a seven-section selective relay which cuts out the bad cables in case any trouble occurs between these two stations. On all other feeders we use standard makes of circuit-closing inverse-time-limit relays.

When a ground or short circuit occurs on a cable or aerial line, a test is made for location as soon as possible. If the ground or short circuit is of such high resistance that a good test cannot be made, the resistance of the fault is decreased either by further breakdown from testing transformer, or by reduction with 600-volt direct current. The location is then made by means of a slide-wire bridge using the loop method. The chief causes are mechanical injury to the cable, defective joints, water in the cable (probably caused by a previous breakdown somewhere near this same location) and high-voltage disturbances, cause unknown.

From Pacific Light and Power Corporation,
Mr. H. A. Barre, Elec. and Mech. Engineer.

The arrangement of the high-tension distribution has been such that it has been possible to operate alternately with the grounded neutral system and the ungrounded delta system. The experience with the ungrounded delta system has been so disagreeable that we have made up our minds that under our conditions a grounded neutral system is essential.

The determining conditions seem to be the number of miles of line and the capacity of apparatus connected to the system.

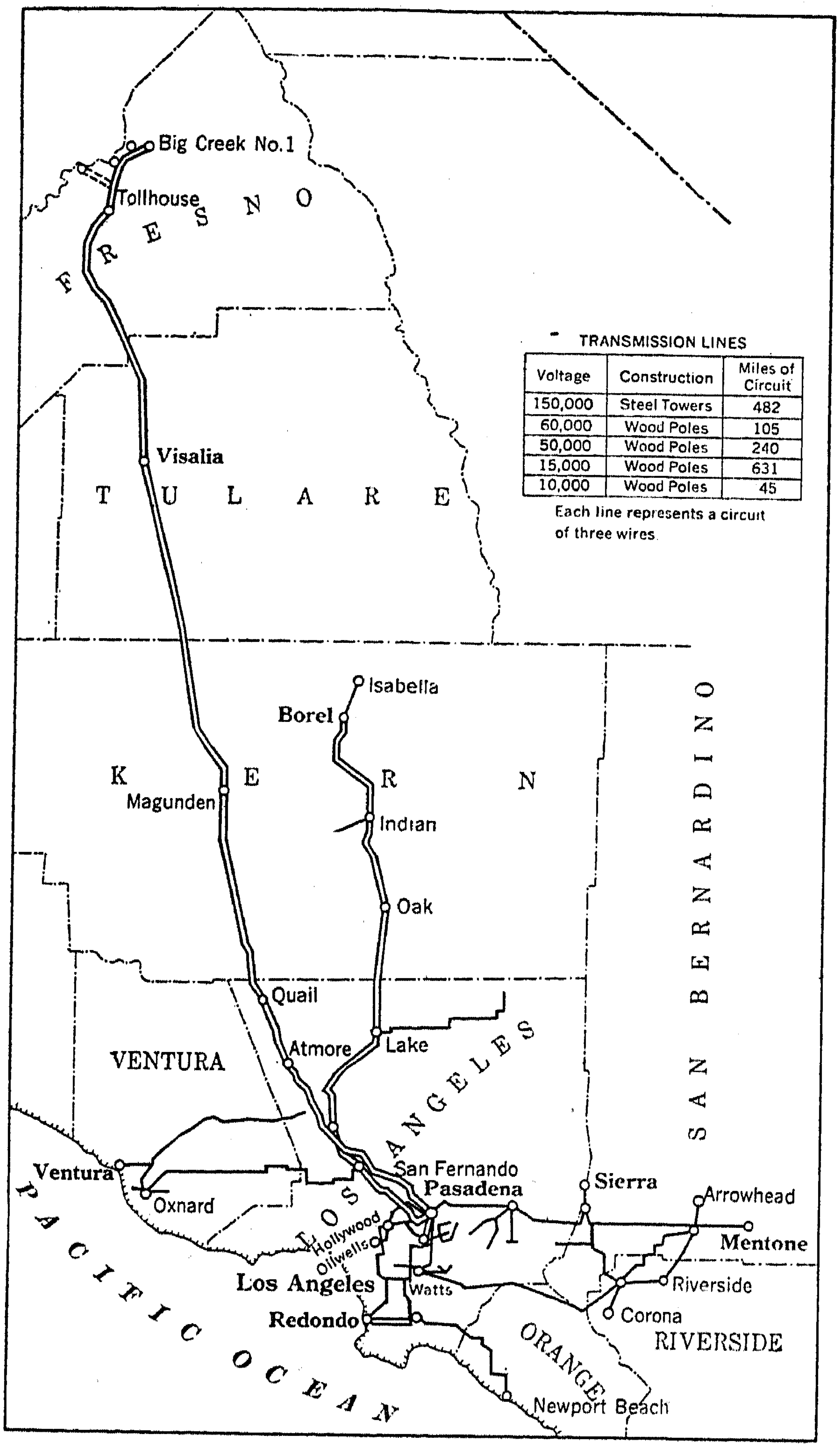
The business of this company consists of supplying power to the company's commercial distribution, which covers all classes of load and includes some 15,000-volt underground cable; and of furnishing service to two large railroad companies, each of which has a maximum demand of about 25,000 kw. The total system peak load for the past year was 76,000 kw. at the generating stations.

The 150,000-volt, 240-mile (386-km.) line from Big Creek is served through delta-star connected transformers at the generator end, with the neutral of the high-tension side grounded, and delivers power through delta-delta connected transformers at the receiving station. One-half of these latter lowering transformers have a secondary voltage of 15,000 volts. The remainder have a secondary voltage of 60,000 volts. The reason for this arrangement is that the base of the company's distributing system is a very extensive 15,000-volt network. The close-in parts of this net work receive power from the substation directly at 15,000 volts. The remote parts are fed with 60,000-volt feeders.

The 15,000-volt network, including the lines of the two railroad companies, embrace about 1600 miles (2574 km.) of line. The 60,000-volt system at the present time has about 85 miles (136 km.) of line.

Connected to the 60,000-volt system through compensators are about 300 miles (482 km.) of 50,000-volt line. Fed from this line are about 45 miles (72 km.) of 10,000-volt lines, and 45 miles (72 km.) of 15,000-volt lines, which are not otherwise connected to the net work. These 10,000-volt and 15,000-volt lines were not connected during the time of trouble with the ungrounded delta system which is described later.

On account of the fact that it was desirable to make the lowering transformers of the Big Creek system of the same design for both voltages so that they could be connected in series for 60,000 volts or in parallel for 15,000 volts, the 60-kv. and 15-kv. systems are in phase, hence they require delta-delta transformations at the remote points where the 60,000-



TRANSMISSION LINES OF PACIFIC LIGHT AND POWER CORPORATION

volt feeders deliver to the 15,000-volt network. This precluded the possibility of a grounded star connection at the latter points of transformation.

Previous to the advent of Big Creek, the 15,000-volt system had been fed from a 40,000-kw. steam turbine plant of which the neutral was

grounded. After Big Creek commenced service, this steam plant was needed only in emergencies and over peaks and the opportunity for establishing the ground through it was lost except during such hours as it might be operated. This left the 15,000-volt network without an established neutral, and it was found that whenever any trouble occurred which involved the accidental grounding of a 15,000-volt wire, the flow of charging current was sufficient to set up very serious surges in the system. These invariably caused breakdowns at more than one point on the system, sometimes three or four points, and the damage to the service and apparatus became a matter of most serious concern. These breakdowns were usually flash-overs or punctures of line insulators or bushings of transformers or switches.

It happened that while this condition existed, a new station was being built at Vernon, in which was being installed, amongst other things, a bank of three 5000-kw. transformers with a voltage ratio from 60,000 to 15,000. As an experiment, the 15,000-volt side of this bank of transformers was connected in star with the neutral point grounded, and the bank connected to the 15,000-volt bus bars. The 60,000-volt side was delta connected, and being, therefore, out of phase with the 60,000-volt bus, was left idle; in other words, an idle bank of transformers having closed-delta secondary was used to establish the grounded neutral on the 15,000-volt system. This bank had a very large capacity, full load being something like 600 amperes.

It was found that this effectively eliminated the surges and that after its installation whenever line trouble occurred the effects were localized in the section affected, and in practically every case the system of operation employed to sectionalize the net work, both automatically and manually, has served to protect the service. Some troubles have occurred on the 60,000-volt system, but since there is a ground established to it by connections to another plant, they do not at the present time appear serious.

This is largely due to the fact that the 60-kv. system is of comparatively small extent and when it grows, a system of connections to establish a grounded neutral of large current carrying capacity will be necessary.

From the foregoing experiences, our conclusions have been that under our conditions on a large system, the power stations should always be operated with a grounded neutral connection on the line side of the transformers. The generator side should be delta connected. At the receiving stations and distributing substations the delta-delta system is preferable.

We have not found the installation of resistance in the neutral of any advantage. The difficulty of making a good ground answers the resistance question.

On the 150,000-volt Big Creek lines, accidental grounds are handled as follows:

When the operator at the power house sees the recording ground ammeter showing a ground, he reduces the generator field by cutting in a special rheostat installed for this purpose. As soon as the ground ammeter drops back to zero he cuts out the resistance and the voltage comes back to normal, and the automatic voltage regulator takes control. This resistance is not cut out all at once, but the time which elapses from the time the arc breaks until normal voltage is restored, is from five to ten seconds.

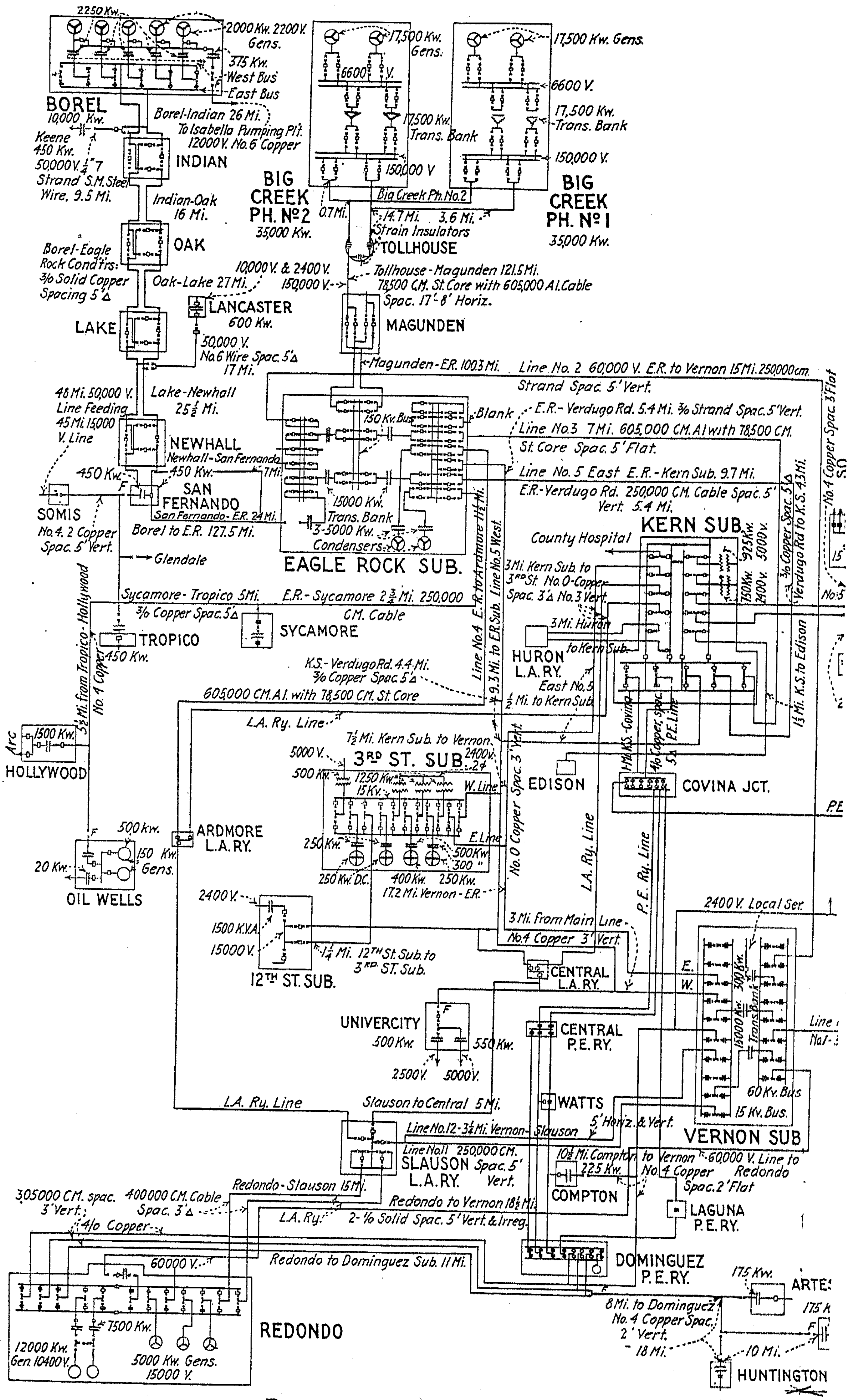
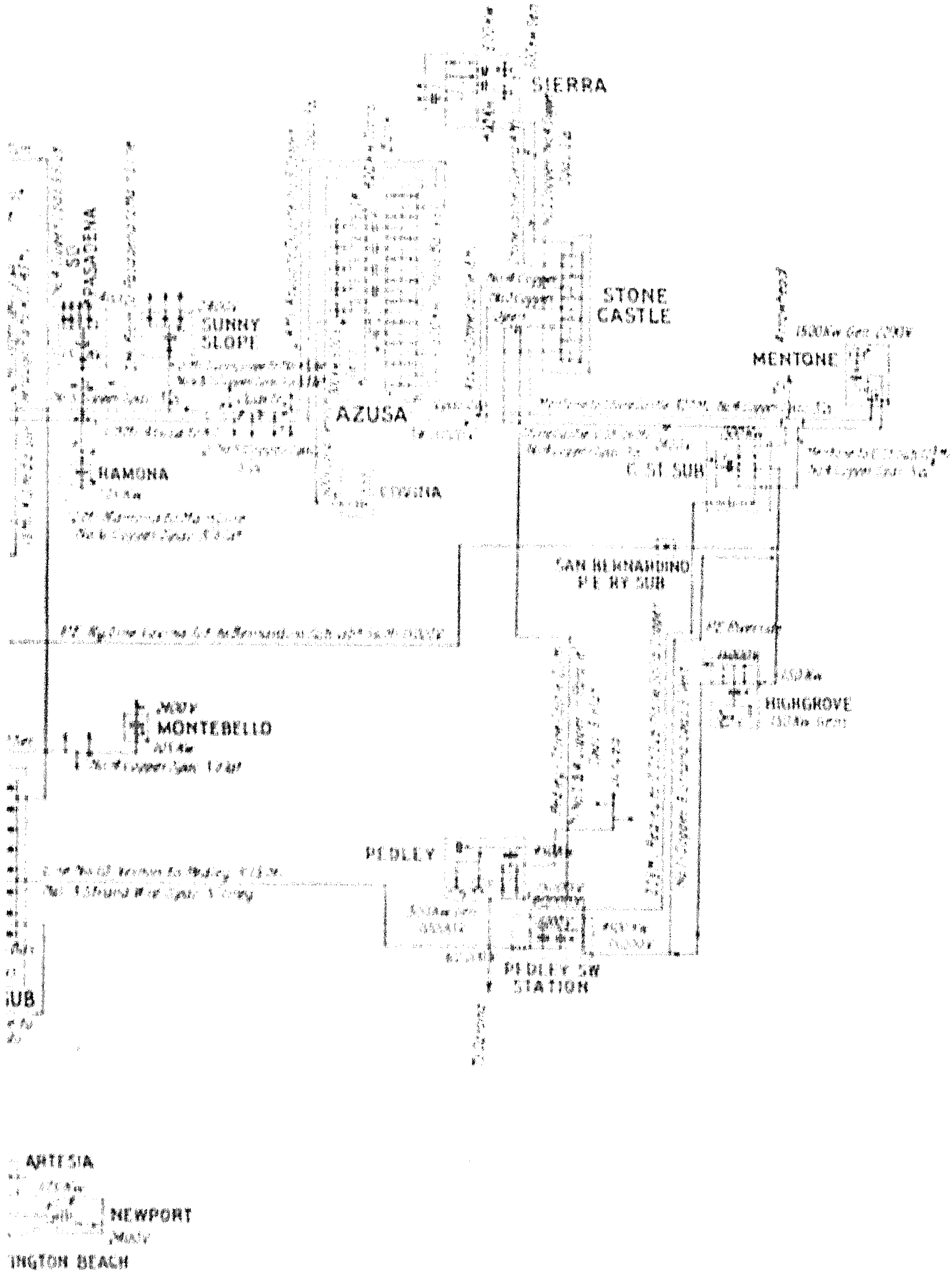


DIAGRAM SHOWING THE DISTRIBUTION SYSTEM



OF THE PACIFIC LIGHT AND POWER CORPORATION

At the receiving station at Eagle Rock the operator kills the field of condensers at once by opening the circuit of the automatic voltage regulator. As soon as he sees that the power house has recovered its stability and the voltage is coming up again, he closes the regulator circuit.

Governors at the power house must take care of the speed when the load is dropped. They always do this.

For the remainder of the system on those lines which are controlled by automatic circuit breakers, the switches are closed after opening on trouble, and if the short circuit or ground is still on the line, the switch is left open and men sent out to find the trouble. Where the switches are not automatic, the above operations are performed manually.

On the 150,000-volt system from Big Creek, the troubles are entirely of two kinds:

First, trouble arising from the human element of which three cases have occurred.

(a) A man digging a well put in too heavy a charge of powder and blew some debris into the line.

(b) A tree was left standing too close to the line and in falling a ground was caused.

(c) A farmer drove a hay stacker with derrick erected at a height of some 36 ft. (10.9 m.) above the ground into contact with the line.

Second, the other and more frequent cause of trouble, of which some twelve or fifteen cases occur each year, is the spilling over of insulators on the middle half of the line. We have not been able to determine the cause of these spillovers or locate any operating or climatic conditions which would indicate their origin. They seem to occur at all hours of the day and night and under all weather conditions, but are absent from the end quarters of the line.

Outside of the 150,000-volt system, the greater number of troubles occur from personal interference, either accidental or malicious, of both employees and outsiders.

On a system containing so many miles of lines and nearly 100 substations, the opportunities for misunderstandings and mistakes are many. This is intensified by the fact that the operation of the lines and substations are under the control of three entirely independent corporations.

Another cause of trouble is the usual one of washing out of lines during floods and similar accidents, depending on the weather.

A considerable number of interruptions have occurred by reason of the continued failure of a certain class of pin-type insulators on the 50,000-volt lines, which have been in operation about ten years. There seems to be a continuous deterioration or weakening of these insulators, which becomes noticeable in those parts of the line where the weather conditions are most severe.

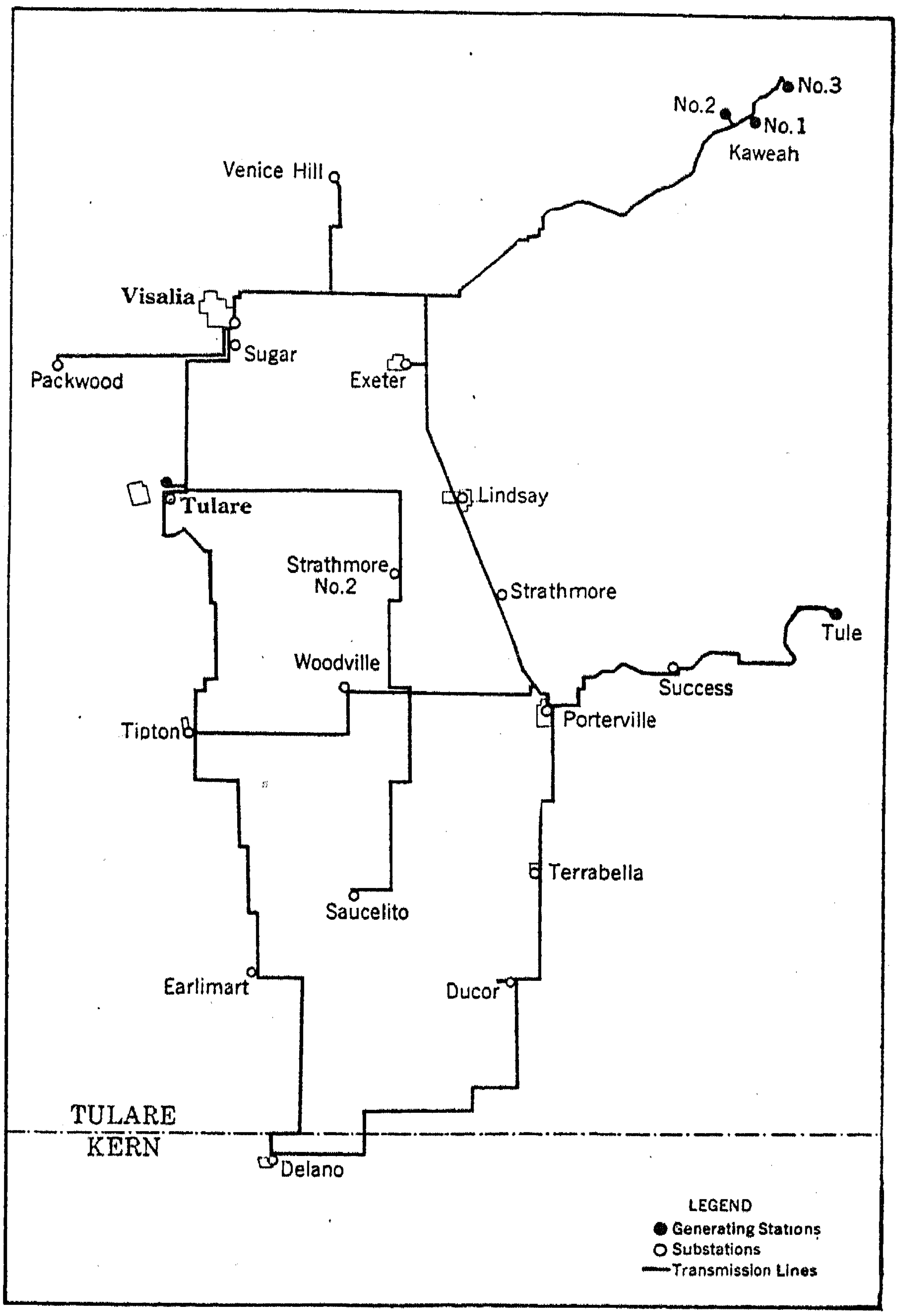
The suspension insulators used on some of the distributing lines have caused a number of failures, although careful inspection of the Big Creek line has so far been successful in eliminating the defective insulators in time to prevent trouble.

The only other serious cause of interruption is the combination of summer fog and dust, causing surface leakage over the insulator, which carries sufficient current to set the pole on fire. In the last few years, interruptions from this cause have been practically eliminated by the expedient of electrically connecting the insulator pins, which are of iron.

No complete detailed analysis of these various kinds of trouble has been made, so that I am not able to give you more than the above generalization.

From Mt. Whitney Power and Electric Company,
Mr. Fred G. Hamilton, Supt. W. Div.

This company is operating practically 200 miles of 33,000-volt transmission lines. The lines are arranged in the form of a figure eight and are fed by four hydroelectric and two steam plants.



TRANSMISSION LINES OF MT. WHITNEY POWER AND ELECTRIC CO.

The neutral is grounded on each hydroelectric plant, but there is no ground at the steam plants or any of the substations.

The elevation of the hydroelectric plants is practically 1150 ft. (350 m.) while the substations are located at an elevation of 350 ft. (106 m.)

It has always been our method of operation and we have no data upon non-grounded operation. We have experienced no particular difficulties particularly chargeable to the grounded system. We have had grounds

and short circuits on the transmission line which are cleared up by cutting out the faulty section, by trial, between two substations. [illegible] is controlled by a load dispatcher at the [illegible] station.

This system gives us very efficient service and the occurrence of interruptions are only of short duration. Since our voltage is comparatively low and we have had no experience with the ungrounded system, we are not in a position to give comparative data which would be of much assistance. For our voltage we feel that an ungrounded system would probably give us as good service as our grounded system.

From The Toronto Power Company.

Mr. F. G. Clark, Chief Engineer.

The question of grounded or ungrounded neutral can be considered from different points of view.

Where drainage of accumulated electrostatic charges is required to avoid excessive d-c. potential, grounding is very effective and will drain off all such charges to earth, while on ungrounded systems this will have to be taken care of by the lightning arresters. This phenomenon is very unusual in the northern part of this continent, and is usually safely taken care of by the lightning arrester.

Continuity of service can be obtained [illegible] with either of the two systems, depending entirely on local conditions.

Grounding should be applied:

Where a reliable selective relay protection is available for cutting out a faulty line without causing a serious interruption.

Where the lines have to be operated in parallel on the high-tension side and where the line insulation is unreliable.

In this case grounding will prevent the spreading of a break-down on one phase of one line to other phases of another line thus avoiding a long total interruption.

Where this high insulation exists so that other phases can stand momentary over-voltage due to one phase flashing to ground or where the lines can be operated sectionalized from the high-tension side, the spreading of a fault from one line to another due to the momentary voltage rise on the sound phases as occurs on an insulated system, is not to be feared. Accordingly nothing can be gained from grounding in this case. On the contrary, grounding may cause unnecessary disturbances and interruptions, whenever one phase only is affected which would be particularly detrimental to continuity of service where no reliable selective relay protection is available.

The decision on the question of solid or resistance grounds should be guided by the line insulation and by the ability of the apparatus to withstand short-circuit strains. Where low and unreliable insulation on the line is the prime object of grounding and where the equipment is built to resist effectively any short circuit strains, solid grounds should be used.

Where, however, the insulation is high and reliable and where the equipment may be somewhat mechanically weak, a ground resistance will be desirable to reduce the mechanical strain of single-phase short circuits.

I would further advise that our transmission system from Niagara Falls to Toronto is composed of four circuits operating ungrounded at 60,000 volts. The transformers on either end are delta connected.

From Puget Sound Traction, Light and Power Company,
Mr. G. E. Quiman, Engineer, Seattle Division.

The four hundred odd miles of high-tension transmission lines of this company are delta connected and operated without grounds.

It is our opinion that probably the chief advantage of grounding the neutral of a high-tension transmission system, is that it eliminates most of the trouble experienced on an isolated system from arcing grounds. The principal disadvantage of grounding is that line trouble more frequently results in interruptions to service. It is our experience that the insulating qualities of wood poles and cross arms make it possible to retain a line in service until the defective point is located and frequently until arrangements can be made to take the line out for repairs.

Even insulator failures resulting from arcing grounds seldom cause serious service interruptions where the lines are carried on wood poles.

We are inclined to believe that where all important business is served from duplicate transmission lines, the grounded system is preferable, but where single lines have to be depended upon the isolated system makes possible greater continuity of service.

From The Colorado Power Company,
Mr. Norman Read, Asst. General Manager.

The Colorado Power Company is at present operating both its 100-kv. transmission and 13-kv. distribution systems connected in delta and with no artificial neutral.

From The Montana Power Company,
Mr. H. H. Cochrane.

This company operates ungrounded, and believes this method preferable. Telephone operation is very satisfactory.

The typical protection for two transmission lines in parallel consists of three-pole overload relays at the generating station end of the line, operated by three current transformers in each line, and three-pole reverse-current relays operated by three current transformers and potential transformers in each line. The system has sufficient line charging current to trip relays when one wire of the system is grounded.

From Utah Power and Light Company,
Mr. Markham Cheever, Chief Engineer.

From our principal generating stations power is transmitted at 130,000 volts to a central substation near Salt Lake City. At this substation the voltage is reduced to 44,000, and numerous feeders make connection with an extensive and complicated network of 44,000-volt lines. Everything is now operated with neutral ungrounded and we see no reason for changing the 130,000-volt system, since up to the present time there have been during two year's operation, practically no operating difficulties.

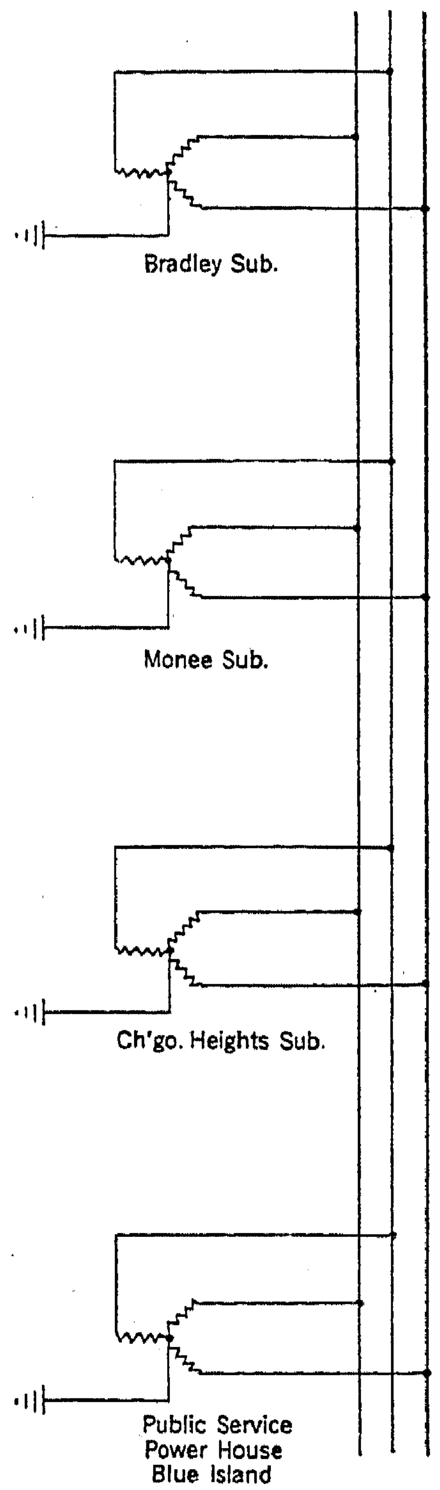
Upon the 44,000-volt system we are considering the installation of a suitable grounding compensator located at the main central substation for the purpose of facilitating automatic sectionalizing of disabled lines and for the reduction of high-voltage strains.

Our earlier experience in this territory with 44,000-volt systems of moderate sizes indicated the advisability of operating with neutral un-

grounded, since there were many cases of grounds which would clear themselves without disturbing service and some cases of dead grounds which permitted the continuance of operation until repair could be made. During the winter of 1912 and 1913 a number of systems were paralleled and since that time many extensions have been made. With the enlarged system we are finding that practically all cases of grounds develop into serious trouble and it is often difficult to localize the disturbance.

From the Chicago and Interurban Traction Company, Mr. Robert J. Bell, E. E.

We have a 33,000-volt three-phase 25-cycle transmission line, extending from the Public Service Co. power plant at Blue Island, to Bradley Ill., a distance of about 45 miles (13.7 km.) This line consists of three No. 4 hard drawn copper wires placed on 35-ft. (10.6-m.) cedar poles spaced 110 ft. (33.5 m.) apart.



BRADLEY SUB-STATION TRANSFORMERS 1950-430 VOLTS. POWER HOUSE TRANSFORMERS 9000 -33000 VOLTS

We have three substations on this line with one 500-kw. synchronous converter in each of these stations. The Bradley substation has, in addition to the converter, a 500-kw. frequency changer, 25 cycles to 60 cycles.

Our transformers are Y-connected on the primary in all the substations. At the power plant they are Y-connected on the secondary side.

We have a telephone line on the same poles, but do not experience any serious trouble. There is some noise but not enough to interfere with service. This line is transposed at every fifth pole. The neutral connection at the transformers is grounded, and we have not experienced any trouble therefrom. We have experienced one great advantage by grounding the neutral, that is, in case of line trouble, where one of the phase wires becomes grounded, we are able to test out and find what phase it is, then have the disconnecting switches pulled out on this phase at each end. We are then able to operate on the remaining two wires by the use of the grounded neutral.

This system has saved us a great number of hours of shut-downs and we have had no trouble caused by this system of operation.

As to the advisability of grounding the neutral, while it may not work successfully on all systems, I think it worth while to try it out, especially if the transformers are not loaded too heavy.

We operate grounded at the substations and at the power plant.

We lost some insulators during electrical storms (which having the neutral grounded may encourage). All our trouble has been from direct lightning strokes.

It makes our telephone line a little noisier when we are working on two line wires than otherwise.

A general layout of the line with the transformer connections is shown herewith. We have an overload relay on our oil switch which is set to trip out on normal overload, and we make use of the current to ground when we are using two line wires.

These grounds are cleared by linemen sent over the circuit. The causes are various, but very frequently can be traced to a broken insulator. I think no current flows to ground through the ground connection but have never made any test to that effect.

From Alabama Power Company,

Mr. W. E. Mitchell, Operating Manager.

Our experience here in Alabama has caused us to become firm advocates of the grounded neutral on our high-tension system, and grounded solidly without any resistance whatever. This is based on about nine months of operation with it ungrounded and a year's operation with it grounded. This matter is discussed somewhat briefly by Mr. Dewey and myself in a paper which we read before the S. E. Section of the N.E.L. A. in September of this year. We found that our insulator troubles in the way of breakdowns and flash overs were much worse and much harder to locate and control when ungrounded than when grounded. Grounded neutrals also made it possible to use the selective relays for cutting out immediately any section of line which might be in trouble. The grounding of the neutral turns any arcing ground immediately into a phase-to-neutral short circuit, which is much simpler to handle and to relay for than an arcing ground on an ungrounded system.

From The J. G. White Engineering Corporation,

Mr. C. D. Gray, Asst. Electrical Engineer.

My personal opinion is that systems up to about 38,000 volts should be operated with isolated-delta connections, although this depends upon the local conditions under which the system under discussion might be connected. For systems above 38,000 volts I believe the star connection with grounded neutral to be the best, although in this case also the local conditions would influence a decision as to whether it should be star or delta. The locality in which the line is to be operated I believe has a great deal to do with it, and also the chances of interference with telephone, telegraph and other systems of this kind.

Our experience has been that the delta system has less influence on telephone and signal circuits than the grounded-neutral connected system. A great disadvantage of the star-connected grounded-neutral system is the fact that the circuit breakers are thrown out on trouble on any one of the three wires of the system, and that it is practically impossible to operate with one wire down, or with one transformer out of service in a bank of three, unless the conditions of grounding are very favorable, where as with the delta system the open delta-connections of transformers can be used temporarily at least without causing a great deal of trouble.

Another point in favor of the star-connected grounded-neutral system is the fact that trouble on the line can be located better by means of the Nicholson or other similar testing method. The line insulation has been

so improved in the last few years that it is now possible to operate delta connected whereas previously it was not possible on account of the insulators, it being necessary to reduce the potential to ground in order to favor the insulators.

With regard to the operation of three-phase systems, I agree very well with the paper of Messrs. Jollyman, Downing and Baum, given before the Institute on May 29, 1914. This would be especially true with any system operated with pin-type insulators similar to that of the Pacific Gas and Electric Co's. system.

In conclusion I would say that I am not greatly in favor of one system over the other, but that the local conditions would largely influence a decision in the matter, and it seems to me that it is more a matter of experience from operation in any particular section of the country rather than the result of theoretical decision.

From Pacific Gas and Electric Company.

Mr. J. P. Jollyman, Engineer Electrical Construction.

The experience of the Pacific Gas and Electric Company with the grounded neutral has been covered in considerable detail in the paper by Messrs. Jollyman, Downing and Baum, presented to the Institute in 1914 (TRANSACTIONS A.I.E.E., Vol. XXXIII, pp. 767). Our further experience with this system has confirmed the opinions expressed at that time.

From Mr. Charles E. Waddell,

Consulting Electrical Engineer.

The two high-tension systems with which I am most familiar do not ground the high-tension neutrals; these systems are the North Carolina Electric Power Company, which serves Western North Carolina and which operates at 66,000 volts and 6600 volts, and the Florida Power Company which serves the west coast of Florida in the mining district and which operates at 60,000 volts.

My inclination, which is tending toward a fixed opinion, is that it is possibly wise to ground the secondary system of small substations supplying consumers regardless of the secondary voltage, be it even as high as 2000, the object being the protection of life and property. On the other hand I am forced to conclude,—certainly for this vicinity,—the grounding of the neutral of high-tension transformers at the main substations would be a menace rather than a protection. As you are fully aware, the recent general practise is to ground the secondaries of the instrument transformers used in connection with the switchboards. While this has proved a great protection as far as life is concerned, I have found that the practise has increased the number of burnouts and really interferes with continuous service.

A considerable number of additional replies were received which contained no information of special interest.

An examination of the above replies emphasizes what is perhaps the proper point of view on this subject, namely, the effect of grounding the neutral of a high-tension system will be differ-

ent in different sorts of systems, it may be an advantage in some and a disadvantage in others. Furthermore the effect of grounding through a resistance is different from the effects of grounding directly. Each case must be considered on its merits and most of the probable cases are illustrated by the above replies.

The neutral may be grounded in different plants for various reasons:

(a) To prevent throwing full line potential on other line wires by a ground on one line.

(b) To enable relays to operate quickly and surely or selectively.

(c) To prevent arcing grounds.

(d) To locate breakdowns.

(e) To take the place of one line wire on a three-phase system when this wire may be interrupted. This requires the disconnection of the grounded wire.

(f) To enable grounds to be extinguished by the Nicholson automatic system of grounding through a fuse.

When the ground connection is specifically omitted it is usually to enable operation with one line grounded and thus minimize interruptions.

Actual practise shows that grounding is more often resorted to on high voltage, and in large and complicated systems. Wooden-pole, wooden-crossarm lines below 60,000 volts offer the best chance of operating successfully with one line grounded.

In conclusion attention is called to the very full and illuminating reports of several of the companies sending replies. The thanks of the committee is due to these and the others who have cooperated with the committee in collecting the data reported.

DISCUSSION ON "REPORT OF TRANSMISSION COMMITTEE," CLEVELAND, OHIO, JUNE 27, 1916.

N. A. Carle: I think that in general it is recognized that higher temperatures occur in transformers, motors and generators at altitudes above 600 feet than for the same loads at sea level. At the present time, I understand, the Standards Committee of the Institute is trying to determine a suitable corrective factor or formula to meet this condition.

M. O. Troy: Mr. Carle has correctly summarized the matter when he says that correction for altitude is one of small magnitude.

Operating men, who in the past have bought electrical apparatus with reasonable margins of safety, in all probability have not noticed any effect of altitude, and for that reason so state in their reports. If, however, they had measured their loads and capacities carefully and compared the heating values so obtained with those obtained by the manufacturers—in all probability at lower altitude—they would have found a difference.

In the standardization work of the Institute, we have tried to establish safe but definite temperature limits of operation.

I think there is no doubt that modern apparatus working at sea level to the limits prescribed by the Institute will exceed those limits if the apparatus is operated at the high altitudes under discussion; and if the sea-level temperatures represented a maximum for the safe operation of certain classes of insulation, the temperatures at the high altitudes would go beyond safe allowable limits.

Correction factors, therefore, should be recognized and definitely established by the Standards Committee as soon as reliable data are available.

Peter Junkersfeld: Our experience in Chicago with the grounded neutral covers the past fifteen years. The first experience was the initial installation of the four-wire three-phase system of primary distribution operating at 2300/4000 volts, 60 cycles. This system was extended so rapidly that in a few years it absorbed all of the older single-phase generating stations, and has since been the standard arrangement in the Chicago territory.

Within a year after our initial experience on the 60-cycle system the voltage on the 25-cycle system was raised to 9000 volts and the neutral grounded, which has since then been standard practise on that system.

Both of these systems have grown so rapidly that the experience in Chicago with grounded neutrals has been quite extensive during the past fifteen years as may be illustrated to some extent by the mileage of cable or conductor operated with grounded neutral, which at this date is as follows:

9000-volt,	25-cycles,	3-phase	cables	undg.	485	miles	(781 km.)
20000 "	25- "	3- "	"	"	83	"	(132 km.)
12000 "	60- "	3- "	"	"	158	"	(254 km.)
					726		

2300/4000-volt, 60-cycle single conductor equivalent underground 1518 (2444 km).

2300/4000-volt, 60-cycle single conductor equivalent overhead 7850 (12638 km.)

The reason for stating the last two in conductor miles is that there are a considerable number of single-phase branches connected to the three-phase four-wire circuits. In such cases and also on some other circuits single-conductor instead of three-conductor cable is used.

The 25-cycle 9000-volt system is supplied by turbo-generators ranged in capacity from 12,000 to 30,000 kw. This system is divided into sections, so that the generator capacity connected to the largest section does not exceed 80,000 kw. Three of these sections are interconnected by tie lines with protective reactance coils, while the fourth section is connected to the system by means of underground tie lines about 8.3 miles (13.4 km.) long without reactance coils. Our standard practise is to have the neutral grounded on one turbo-generator of each of the four sections. The neutrals are grounded through iron-grid rheostats having a resistance of $2\frac{1}{2}$ ohms. One of these rheostats is provided for each system section, and is connected between ground and a neutral bus, which can be connected by means of an oil circuit breaker to the neutral of any turbo-generator on that system section.

The neutrals of the 12,000-volt 60-cycle turbo-generators are grounded in a similar manner through iron-grid rheostats having a resistance of three ohms.

The energy for the 2000-volt 25-cycle system is supplied by means of three 5000-kw. three-phase transformers stepping up from 9000 to 20,000 volts. The primary is delta and the secondary is star connected with the neutral of all three transformers grounded solid.

The 2300/4000-volt 60-cycle system is supplied by 25- to 60-cycle frequency changers and 1200-volt to 4000-volt three-phase transformers. The transformers are delta on the primary and star connected on the secondary. The neutrals of the 60-cycle generators and of the frequency changers are all connected solid to ground, and the same is true of the neutrals of all of the transformer secondaries.

The experience with grounded neutral on the above systems has been very satisfactory, the principal benefits having been the following:

1. It insures the prompt automatic disconnection of any faulty feeder.

2. It prevents the existence of delta voltage to ground on

other lines and apparatus in case of a ground on any part of the system.

3. It helps in locating breakdowns of lines and of apparatus.

4. It prevents arcing grounds and therefore voltage disturbances.

It must be noted that the last statement refers to specific conditions. Under some conditions differing from these it may not always be advisable to ground the neutral. I with several other engineers made a rather extensive inquiry a few years ago as to the advisability of grounding the neutral on 33,000-volt overhead lines connecting cities and towns in Illinios. In this case it was decided to install a delta connected system without grounded neutrals, except in such few special cases as might later prove to be advisable. The reasons for that decision were as follows:

1. The general secondary distribution system was four-wire 2300/4000 volts. As this necessitated a star connected secondary on the step-down transformer, acknowledged good practise determined a delta connected primary on these transformers.

2. On account of consolidations, it was necessary to operate in parallel a number of different properties, and because of phase relations it was found most advantageous to have the step-up transformers at the generating stations star connected on the primary and delta connected on the secondary.

3. The argument, that with an ungrounded neutral the system could be operated in emergencies with one phase wire grounded, had considerable weight.

The 33,000-volt lines have been built so rapidly during the four years since the decision referred to was made that they now aggregate 1000 miles (1600 km.) in Illinois alone. These lines are not all owned or operated by the same companies, but in this matter and in many other matters follow the same principal engineering standards.

I will repeat, that on the overhead system the experience is still too limited to draw absolutely final conclusions, but as far as the underground system is concerned, covering a period of fifteen years and the large mileage mentioned, we feel under those conditions that grounding of the neutral has proved a wise course.

E. E. F. Creighton: There are some cases where the neutral can be judiciously grounded, and there are other cases where it is better not to ground it, if the proper precautions are taken. The greatest objection to a non-grounded neutral at the present time is the arcing ground, and the result it gives on the system.

David B. Rushmore: In connection with the installation of the various transmission systems in this country, there has been a continual discussion regarding the relative merits of grounded Y and ungrounded delta transformer connections. As electrical apparatus, and especially lightning arresters, have de-

veloped the situaton has undergone different modifications, so that in some places one and at other times the other connection has seemed desirable.

Transmission systems have, as a rule become high-tension distributing systems, and the network of overhead wires has become greatly extended and the load situation much more complicated. The important question of operating so as to deliver continuous service has brought about the development of automatic relays, so that disturbances may be instantly localized. For this purpose the use of the grounded Y has many decided advantages and, in most cases, at the present time is to be recommended.

N. A. Carle: The preponderance of opinion seems to be against the grounded system. We in New Jersey have a lot of transmission lines there, and have an ungrounded system which is very satisfactory.

J. T. Lawson: The system mentioned by Mr. Carle operates at 60 cycles, 13,200 volts with an ungrounded neutral, and is equipped with an arcing ground suppressor.

Mr. Rushmore, if I understood him correctly, brought out the point of non-interruption to service on a grounded neutral system. With an ungrounded system equipped with an arcing ground suppressor, I think you come closer to this condition than without the use of the suppressor. Instead of having a cable open at both ends thus shutting off the service, with the arcing ground suppressor it is possible to leave the grounded cable in, parallel it with another cable, or take it out, with no interruptions to service.

The action of circuit-opening relays, possibly, with the grounded system may be more satisfactory, but with single-phase arcs to ground I do not see where fine relay adjustment is necessary if the arc is extinguished before it has a chance to develop into a short circuit.

David B. Rushmore: My remarks applied mainly to high-voltage systems, 100,000 volts and over.

John B. Taylor: The detailed experiences contributed on operation of three-phase transmission systems with, and also without, neutral grounded, are of interest and value. The committee's conclusion that for different cases, grounding "may be an advantage in some and a disadvantage in others",—is quite in agreement with previous discussions of the same question.

N. A. Carle: We have a balanced potential relay, and the unbalancing of one phase to ground puts that cable out of business, and we simply get it afterwards on tests, and another cable goes in.

John B. Taylor: You determine that unbalancing, I assume by an arrangement of potential transformers connected to your bus bars and also connected to ground, which means that your system is grounded,—you have a neutral ground on the system,—that neutral ground is made on relatively small potential trans-

formers instead of on relatively large generators, but, technically, the system is grounded on account of the potential transformers connected in Y with their neutral grounded.

N. A. Carle: There is only one connected with the relay which makes an artificial ground through the oil switch.

P. H. Chase: I think I can explain that point. The grounded neutral system is so-called because the ground is of sufficiently low resistance that the current to ground operates a relay on the grounded phase. This is distinguished from the ungrounded neutral system with a suppressor, in that the three potential transformers which are connected in star with the neutral grounded allow only the exciting current of the potential transformers to flow to ground. Though there is this metallic connection to ground, the system with a suppressor cannot properly be classed as a grounded neutral system because the exciting current of the potential transformers is not of sufficient magnitude, and is not intended, to operate the overload relay on the grounded cable.

John B. Taylor: It seems finally to come to a definition of technicalities.

E. E. F. Creighton: If we add to Mr. Taylor's remarks some figures, it may help to straighten out the matter. The current to ground in potential transformers is a small fraction of an ampere. The current that reduces one phase of this system to ground is over sixty amperes. It would take more than forty amperes to reduce it to half potential to ground, and, therefore, I consider the system is non-grounded, even though the potential transformers are connected to ground at the neutral, because they could not in any way maintain the neutral at grounded potential.

H. R. Woodrow: Our experience has not shown that any advantage from surges has been gained by grounding the neutral of the system. The neutral of our sixty-cycle system was grounded more than two years ago and we have never been able to find any difference in surges before and after grounding. The 25-cycle system has never been grounded and we have never had any serious disturbance due to high-frequency surges.

In a case of some 15,000-volt cables, the failures looked rather suspicious of surges, and we therefore grounded the neutral of this system in an attempt to reduce the surges. The result which we have obtained in the last year and a half, since this system was grounded, shows scarcely any difference in the characteristics or number of failures.

In the ungrounded system we have the grounding relay protection with a grounding transformer, which will indicate a ground on any feeder, so that the defective feeder can be taken out of service before it develops into a short circuit.

Edmund C. Stone: The system I am familiar with is a system of about 175 miles of 11,000-volt transmission, three-phase. About fifty miles of that is underground. We find that nearly

all of our troubles originate in the overhead system and set up arcs in the grounds which break down the cable system. I think where the system is entirely cable probably that trouble would be eliminated, but we have a great deal of trouble from arcing grounds originating in the overhead system, which set up voltage disturbances, and in turn break down the cable system. We have decided to adopt a grounded neutral on the theory that saving the cable is more important—the downtown system is all underground— than maintaining continuous service on the overhead system.

So far we have never had a case in five years where we have been able to operate the system with one phase of the overhead grounded. That seems to be the main recommendation for the three-phase system, and I would be interested to know if there are many examples on record where the three-phase system is actually operated and profitably operated, when one phase was temporarily grounded,—that is an arcing ground starts and creates such a disturbance that it puts us out of business until we have isolated the defective line.

Fred L. Hunt: I can tell you of a 66,000-volt three-phase circuit which within the last month operated three hours carrying a 4000-kw. load with one wire broken, the two ends of the broken wire being about 150 feet apart on the ground. The load was carried in this way until a steam plant could be pressed into service to relieve the line.

L. N. Crichton: Mr. Stone's remarks remind me of a case where the records of a transmission company covering a period of several years' operation were studied, and only two cases found where power was supplied with one wire on the ground, and even in these cases the service was finally interrupted before the ground was located. An interruption is not caused by the ground itself but by the disturbances which it creates, a single ground often causing several insulation failures at widely separated points on the system. The principal difficulty in the case of an undgrounded neutral system is that you can not locate an accidental ground, the only way of doing it on a system of any size being by cut and try methods, which with the telephone out of service is a difficult job, and the chances are good that before you get through with the process you will interrupt practically the entire system.

Now this applies only to large systems, say a 45,000-volt system, having 1,000 or possibly 1,500 miles of line. With a small system, no matter what the voltage may be, or with a simple system, say only two parallel lines, with a substation on one end and a generating station on the other end, the chances of operating with one wire grounded are very good. The reason why the large system suffers more than the small one is not because the voltage strains are greater but because there are more weak points which are liable to be damaged. As a rule, these weak points occur in apparatus rather than on the lines, there-

fore, the amount of apparatus connected to the system is of more importance than the number of miles of circuit. If the neutral is grounded the voltage strain will be reduced so that the disturbance will not cause such widespread damage and every ground will be promptly disconnected by the automatic circuit breakers.

R. F. Schuchardt: I suggest that Mr. Hunt tell us in connection with the case he cited, something as to the nature of the soil the wires fell on, whether it was in wet grass, or sandy soil, or what the character of the soil was.

Fred L. Hunt: It was in the Connecticut valley, in western Massachusetts, in sandy soil. The grass and brush in the vicinity were set on fire and we were notified of the trouble by a farmer who said his field was on fire. The wire fence around the field seemed to be charged and showed signs of heavy static discharges.

E. T. Street: We have operated 13,000-volt lines with one wire on the ground, supplying power to our substations until we were able to switch over to another line. It has been my observation when we have had lines on the ground—we have had two wires down within one foot or eighteen inches of the other on sandy soil—that the breakers would stay in. With the ungrounded system we can have wires down without causing any interruption to our system as a whole.

Harold Goodwin, Jr.: As to whether the New Jersey system is a grounded neutral system or not, it seems that the committee might do the members of the Institute a service by defining for future discussion whether we shall consider such a system as grounded or not.

W. A. Carter: We had a case where one wire came down on a 100,000-volt transmission line. We buy our power from the Colorado Power Company. The power station was about thirty-five miles away. With one wire carrying current through the ground at the broken span we were able to get several thousand kilowatts, which added to the load carried by our steam plant was sufficient to carry our evening peak load.

Bernard Price: The scheme with which I am connected is controlled by two power companies, viz., The Victoria Falls & Transvaal Power Co. Ltd., and the Rand Mines Power Supply Co., Ltd., the latter being a subsidiary of the former. For present purposes the transmission and distribution systems of the two concerns may be treated as one because they are inter-connected and are operated as one system. The district is at an altitude of nearly 6,000 feet above sea level and is prone to severe lightning storms during at least six months out of the twelve and the major portion of the system is overhead.

For a system of our type, it is unquestionably wise to earth the neutral. Instances have arisen where a certain portion of the system has become insulated from earth during a lightning storm and the result has always been a very large increase in the

number of faults. Whilst I realize that each scheme should be dealt with on its merits, I find it most difficult to conceive any overhead network in a lightning district which would not benefit by an earthed neutral.

Our experience of running the system with the neutral grounded has been most satisfactory and has shown conclusively the advantages to be derived from such grounding on a system of the type in question. In the early stages of development of the scheme, the system was run with an insulated neutral and the change to a grounded neutral removed many of the difficulties which we had encountered. Since the neutral was grounded instances have occurred where a portion of the system has become insulated at the neutral during a lightning storm and on such occasions a largely increased number of flash-overs has occurred.

Before the system was earthed, any line fault produced heavy surging with consequent flash-over from live conductors to iron work at various points in the switchgear and arrester gear. Since the neutral has been earthed, these troubles have virtually disappeared. When the system was insulated a fault from one phase to earth did not operate the automatic cut-outs but caused the arrester gear to discharge continuously. This continuous discharging heated the water resistances which are connected in series with the horn gaps of the arresters and as a consequence the discharge at the horn gaps became increasingly vicious until finally something had to give way. Frequently the arc at the horn gaps jumped to neighboring iron work, thus producing a short circuit through the original fault. Great trouble was also experienced due to flash-overs at points on switch-gear and apparatus caused by the surging produced by an arcing ground at the original fault.

By grounding the neutral the automatic cut-outs were able to instantaneously isolate the initial fault. Lightning arrester gear was no longer called upon to continuously discharge and flash-overs on switchgear connections and apparatus became a negligible quantity.

It is of course essential that each separate section of the system shall be separately grounded and provision must be made to ensure that when portions of the system become automatically isolated from other portions, they still remain grounded.

The grounding of the neutral is the only means we adopt for preventing a static rise of potential. In the dry season, during which winds are prevalent, serious rises of pressure would no doubt occur if the neutral of the system were insulated but we have experienced no trouble in this respect since the neutral was grounded.

As already mentioned, the benefits which have been derived from the grounding of the neutral have not been solely due to such grounding but have really been the result of the combination of a grounded neutral with the adoption of differential relays controlling the cut-outs.

With regard to the points at which grounding should be introduced, we have found that generally main generating stations serve the purpose quite satisfactorily, the advantages being as follows:

1. The grounding being at the source of supply there is a minimum length of line between the fault and the source of supply, thus decreasing the total impedance to earth and in the case of a large network, this factor becomes important. In some cases it may be found necessary to introduce more than one ground so as to compensate for the high impedance of the lines where these are unusually long. In practise we have found this to be the case.

2. The grounding resistance being at generating stations, is subject to constant supervision and thus is liable to be kept in a more efficient condition by routine inspection and overhaul, and moreover, can be repaired quickly in case of breakdown with a minimum cost.

3. If the step-up transformers at the station be designed with delta-star connections (the low tension in delta), then grounding can be easily accomplished (without the expense of installing a special earthing transformer), by earthing the star point of the high-tension side.

On the question as to whether a resistance should be inserted in the neutral connection, it may be argued that if the neutral is grounded without a resistance, the pressure rise to earth on the two healthy phases (assuming one phase is earthed through insulator breakdown or other cause) is reduced to a minimum. Grounding solidly, however, results on a fault from one phase to earth, in the production of a dead short circuit with consequent danger to switchgear and other apparatus. The principle we have adopted is to insert resistance of a value as low as safely possible, having in view the condition that the current flowing to any fault must be ample for operating the automatic cut-outs. In this connection it may be found necessary to lower the value in order to compensate for the high impedance of long lines as previously explained or, what amounts to the same thing, to instal another grounded resistance at some other point on the particular section of the system. For example, the ground resistance of the Brakpan 20,000-volt overhead network is 14 ohms and quite satisfactory results have been obtained in practise, but in the case of the Bantjes 20,000-volt overhead network it has been found necessary to have two separate grounding points each of 14 ohms and about 13 miles apart. Originally only one ground resistance was provided at Bantjes distribution station (see Fig. 1) and the experiment was tried of reducing the resistance until ultimately this was brought down to 8 ohms. No marked improvement was however effected owing to the high impedance of the lines between Bantjes and Luipaardsvlei and finally, another grounded resistance was installed at West Rand No. 2. Although no trouble has since been experienced, we are

awaiting the results of another lightning season before forming a definite opinion.

In regard to the construction of the resistance, our experience is confined to two types, viz., metallic grid resistances and water resistances and has shown that water resistances are undoubtedly preferable to the metallic type. The latter are liable to burn out in the case of a sustained fault on the system, *e. g.* high resistance fault to earth. This results in great inconvenience especially

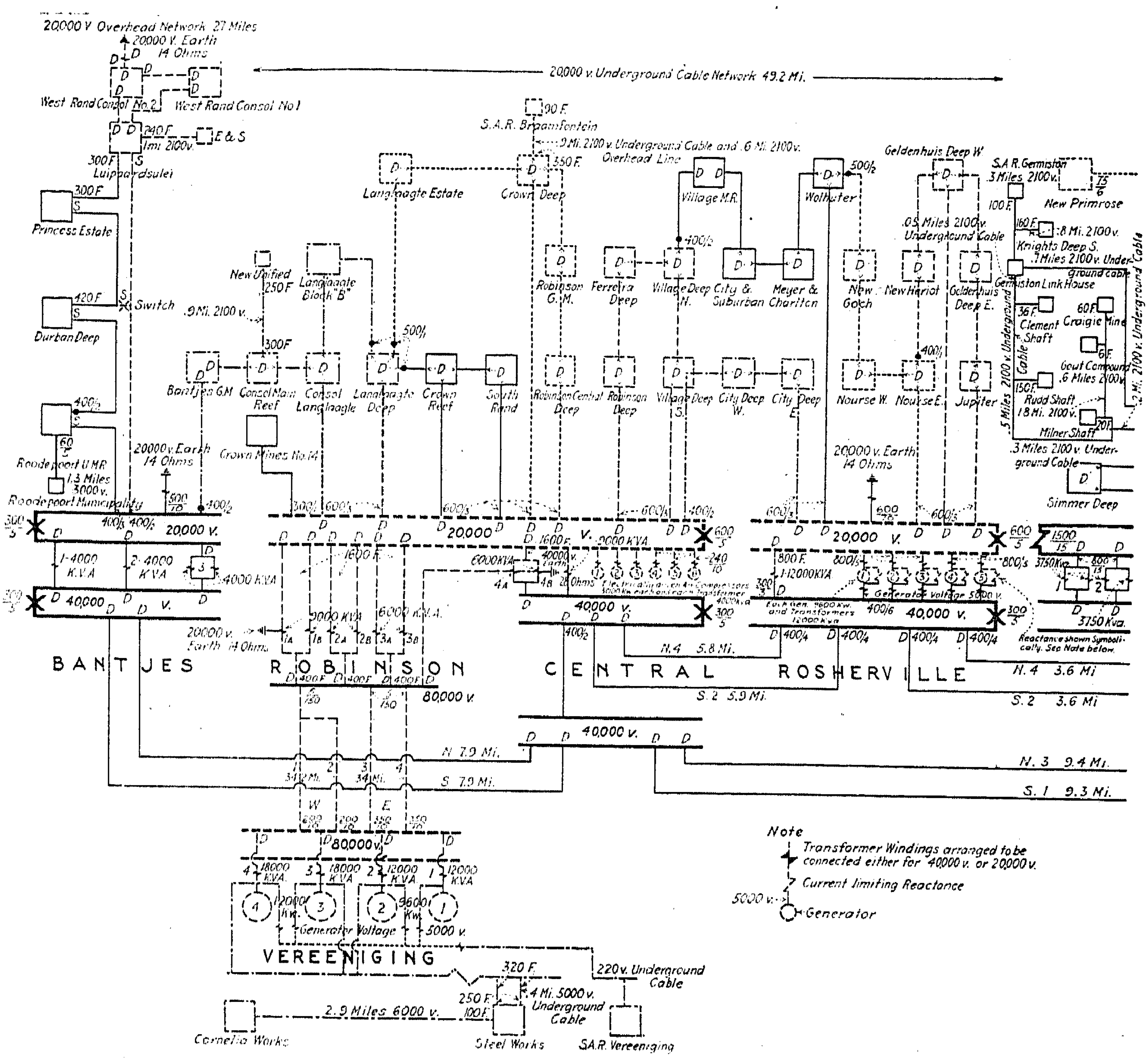
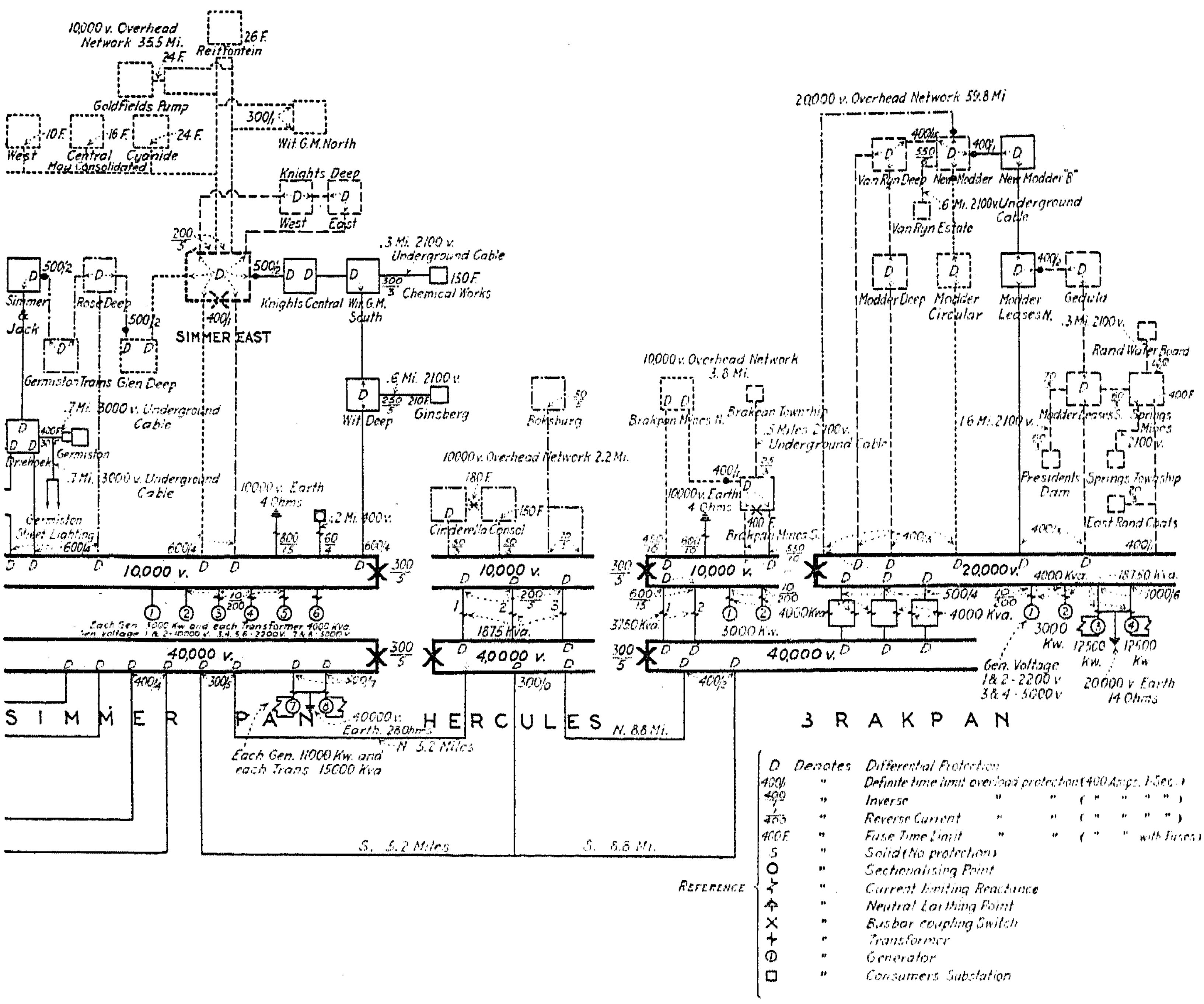


FIG. 1—DIAGRAM SHOWING SECTIONALIZATION OF SYSTEM OF 3-PHASE

if it occurs at the commencement of a lightning storm, as the benefit of the grounded neutral is thereby eliminated for the remainder of the storm. We have experienced no trouble with the water resistances but care must be taken to ensure a sufficient body of water and also to provide for a large metallic surface on the entering terminal so as to prevent undue heating and possible boiling of the water. The water resistance we use consists of a large tank about 7 ft. high and 12 ft. in diameter having a submerged terminal of considerable area suspended from an

insulator on an erection over the water. Such resistances are placed outside on the ground without housing.

We find that metallic grids require constant supervision whereas the water resistances can be left for a period of six months or more without the value of the resistance altering 10 per cent. The resistance moreover can be varied at will with comparative ease and in first cost is considerably less than the metallic type unless very large resistance values are required.



THE VICTORIA FALLS AND TRANSVAAL POWER COMPANY, LTD. 50-CYCLES.

In reference to the earth connection, it is our practise to connect the earth side of the resistance to the station main earth and this has proved quite satisfactory, as in all cases the latter tests out at less than 0.2 ohms.

No difficulty is experienced in obtaining a good earth at power stations as all our stations are associated with a large expanse of water and large metallic plates sunk in the water provide a good earth at all times of the year.

The combination of an earthed neutral (through resistance)

with the differential system of automatic cut-outs has greatly reduced the insulator troubles.

It must be remembered that the majority of our insulator troubles are caused by lightning and as the system is subjected for nearly six months in the year to very severe lightning effects, the matter is of much importance. Owing to the combined action of the earthed neutral and the instantaneous operation of the differential relays the lines which trip out due to lightning flash-overs are in the majority of cases, fit to close it again, because the arc at the insulator has not had time to permanently damage the insulator.

Moreover, we find that the number of insulator faults is considerably increased if the system be run during a severe storm with the neutral ungrounded, due no doubt to the secondary surging which is set up finding out the weaker insulators.

Our experience is that no disturbance to telephones is produced, providing the windings of the earthing transformer are star-delta. We find that we can safely ground the neutral at two distant points with only a small interchange of current and no secondary effects.

If the system is not earthed through a star-delta transformer very violent disturbances are produced on all telephone circuits in the neighborhood of the transmission lines.

Fig. 1 shows the electrical layout of the high-tension lines and apparatus and also the location of all protective devices, current limiting reactances and points of earthing.

It will be seen that the whole system is subdivided into a number of separate networks each laid out on the ring-main principle, thus ensuring at least a duplicate supply to every consumer over divergent routes.

Practically all lines are equipped with Merz-Price differential gear but main feeding points and certain sectionalizing points are equipped with difinite time-limit overload relays, also nearly all generators and all transformers are differentially protected.

Our experience has clearly demonstrated the remarkable discriminating qualities of the differential method of protection and owing to its simplicity and rapidity of action, every piece of faulty apparatus, whether it be a line transformer or generator, is instantaneously isolated with minimum disturbance to the system. It is a feature of this method, however, that individual pieces of apparatus are separately protected and as a consequence a fault on the busbars does not come within the control of the differential relays. Such faults are or should be extremely rare but in order to limit their effect upon supply, the networks are divided up into sections, each section being under the control of definite-time-limit relays at the points where it is fed and where it is inter-connected with neighboring sections. Inverse-time-limit overload relays are in use at a few points where discrimination with other relays is not required. Our experience has proved that on a large power system such relays are of little value as

a discriminating device. Reverse-current relays are in use on a few points such as generators not provided with differential protection and isolated lines not forming a part of a ring-main network and not differentially protected.

It will be noticed in Fig. 1 that the setting of the definite-time-limit overload relays at different points on a network is such that under heavy fault conditions the network is automatically sectionalized, each section capable of a separate existence, *i. e.*, each of these sections has sufficient feeders to deal with its particular loading. These conditions apply to the worst type of fault, namely, a busbar fault at a substation, all feeder faults being dealt with instantaneously by differential protection and without operating overload relays at other points.

In the event of a sustained fault on consumer's premises the substation transformers are tripped off by the simple device of a small fuse inserted in the secondary circuits of the differential relays. This fuse blows with small time element and brings the instantaneously acting differential relay into operation thereby tripping the transformers without operating overload relays at other points on the system. Faults of this kind frequently occur and the supply to the consumer's fault is always isolated without affecting the supply to others.

We use the current flowing to ground at the neutral connection to indicate when a fault to earth occurs. For this purpose a recording ammeter is connected to the secondary side of a current transformer in the earth connection. The results obtained are purely qualitative.

From tests taken with the oscillograph, we have found that under normal operation the magnitude of the current flowing to earth through the neutral is relatively small and of no practical importance.

We have also found that with the neutral earthed simultaneously at two different points, the interchange of current is not appreciable enough to be serious. For example on the 40,000-volt system with the neutral earthed at Simmerpan through 28 ohms, the r.m.s. value of the current was found to be about 1 ampere and the current flowing through the neutral of the Simmerpan 10,000-volt network (neutral resistance 7 ohms.) less than 0.2 amperes.

The oscillogram of the former showed the presence of at least the 13th harmonic and the latter showed the presence of at least the 23rd harmonic.

With the neutral of the 40,000-volt system earthed at two distant points, we found the presence of a comparatively large amount of even harmonics, the 6th being predominant and over 20 per cent of the fundamental in value and in phase with it.

The following is a short description of the various types of relays in use on the system:

Differential Relay. This device as used on our system is a three-phase three-pole relay consisting essentially of a three-pole armature rotating in a three-pole field system.

The latter is energized from the secondary side of the differential protective current transformers and causes the movement of the armature.

The armature in its rotation releases a weighted contact arm which closes the switch-tripping circuit.

Definite-Time-Limit Overload Relay. This relay is made in two parts, one part consisting of an overload relay and the other comprising the definite-time-limit mechanism.

The overload relay is similar in design to the three-pole differential relay, excepting that the impedance of the coils is much greater.

The definite-time-element portion commences to operate when a d-c. circuit is closed by the overload portion which starts the clock-work mechanism. After the pre-determined time has elapsed the relay closes the switch-tripping circuit.

Inverse-Time-Limit Overload Relay. This relay is of the ordinary induction type instrument and the armature, consisting of the usual metal disc, rotates in a field system energized by the secondary circuit of the line current transformers. The relay is single phase and three are required for full protection.

The time element is obtained by varying a tension spring controlling the armature.

Reverse-Current Relay. The reverse-current relay (or more correctly reverse-power relay) is exactly similar in construction and operation to the inverse-time-limit overload relay excepting that it has pressure coils in addition.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED STATIONARY INDUCTION APPARATUS

BY V. M. MONTSINGER

ABSTRACT OF PAPER

The paper falls logically into three divisions: (1) A general review of the principal laws of the dissipation of heat,—radiation, conduction and convection. (2) the development of a simple formula for the effect of altitude on the cooling of surfaces of different shapes, and (3) a general discussion of the method of conducting experimental observations at different altitudes, on three different shaped surfaces.

1. The first division is principally historical in that the most reliable data is given as found from former laboratory investigations, to determine (a) the laws of heat dissipation and (*b*) the effects of various factors on these laws. This is given as a preparatory step to determining the formula in division 2.

2. It is shown in the second division that, where the loss by convection varies as the 1.25 power of the temperature rise and as the 0.5 power of pressure, the "temperature rise" varies as the 0.4 power of pressure. It is then shown that the temperature rise increases, in going from a lower to a higher altitude, at a uniform rate of about 5 per cent for each 1000 meters change in elevation.

Since this applies only to loss of heat by convection, a correction factor is added to reduce this effect when radiation (same in vacuo as in gas) enters into the dissipation of heat. This factor is first expressed in percentage of convection loss to total loss, and then expressed in terms of the developed surface effective for convection, and the envelope surface effective for radiation. This is called the "shape-factor" S. The percentage increase in temperature then is equal to $5\,AS$ where A is the difference in altitude expressed in kilometers.

The above is for a loss unaffected by temperature. Where the loss is in copper windings, an increase in temperature, due to changes in pressure, has the effect of increasing the loss, which in turn still further increases the temperature rise.

It is shown by mathematical treatment that this effect increases the value $5\,AS$ to $5.85\,AS$ for all copper loss. For various ratios of copper to iron loss (unaffected by temperature), the term becomes, close enough for practical purposes, $AS\,(5 + a)$, where a is percentage of copper loss to total loss. The calculated values are then compared with the observed values.

3. In this division the method of carrying on the experimental observations is gone into somewhat in detail.

INTRODUCTORY

WHILE we have reliable data, obtained from laboratory investigations, on the effect of rarefied atmospheres on each of the three principal modes of heat dissipation—radiation

conduction and convection,—yet there does not seem to be any data on, or record of, an investigation to determine this effect when various combinations of the above modes enter into the dissipation of heat, such as we usually have in self-cooled induction apparatus.

Since there is a wide range of these combinations, it would be impossible to make experimental observations on each one. Tests conducted on a few combinations should give us sufficient data with which to make calculations for the remaining ones. Calculations, of course, can be made only by making use of the known effect of altitude on each mode entering into the dissipation of heat; and at the same time we must know fairly accurately

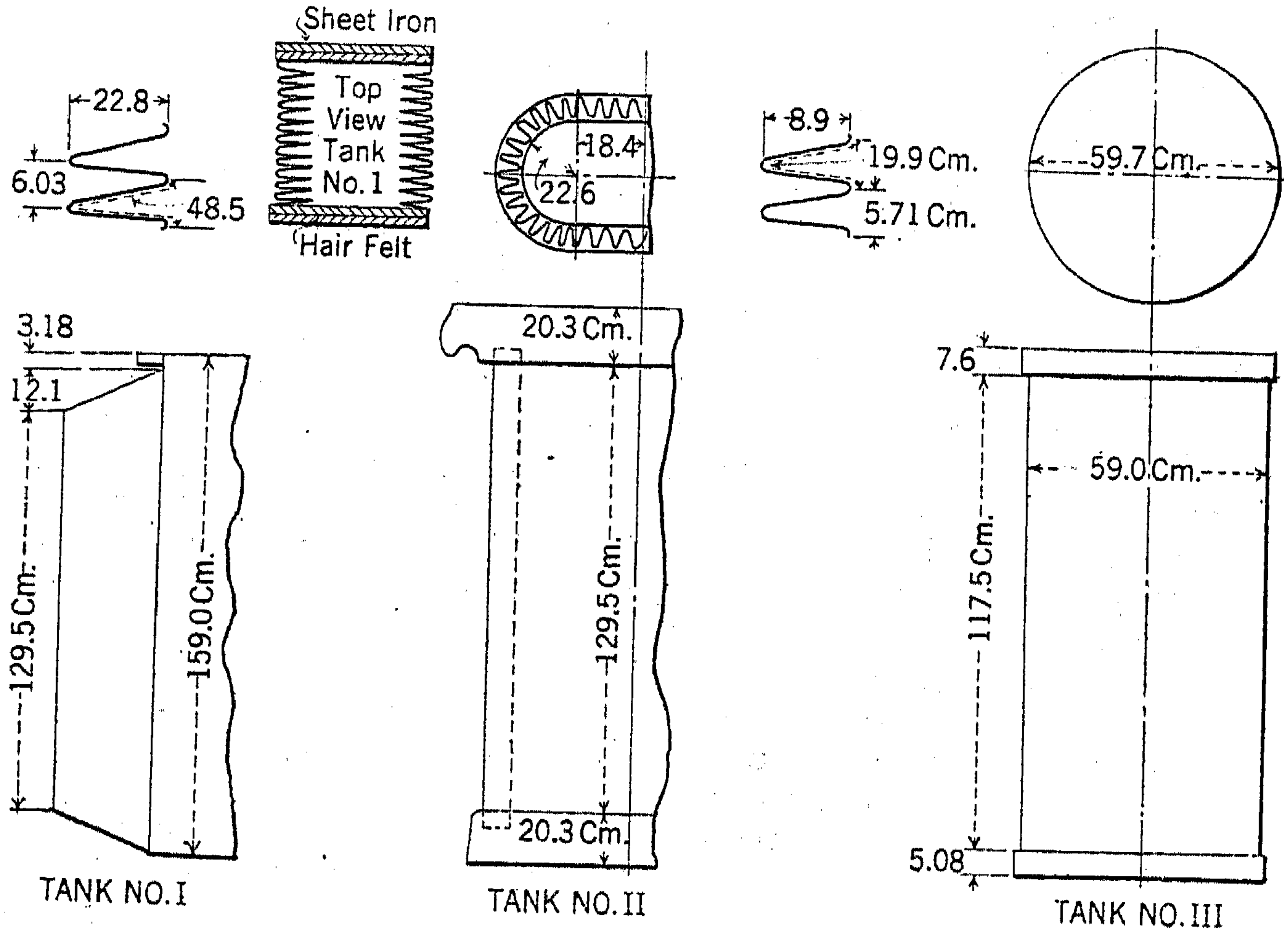


FIG. 1

the proportion of heat emitted by each mode, *i.e.*, we should know its law.

The law of radiation has been accurately determined by Stefan and Boltzman, whence it derives its name, "Stefan-Boltzman law." The law of conduction is well known but need not be considered in this discussion because rarefied atmospheres do not affect it, and for stationary electrical apparatus the dissipation of heat takes place almost entirely by radiation and convection, the latter, excepting for plain surfaces, playing the more prominent part. A law for the convection of heat has been developed and is given by Dr. Irving Langmuir in some of his publications.* While this law holds remarkably well for high

*TRANS. A. I. E. E. Vol. XXXII, Part I, p. 301; Amer. Electrochem. Soc. Apr. 1913.

temperatures, yet for low temperatures, *i. e.*, from 0 to approximately 100 deg. cent., it does not seem to hold very well. This is shown later and in fact is pointed out by Dr. Langmuir himself.

The object of this paper is (1) to give, as found from experimental observations on surfaces of various shapes, the ratio of heat dissipated by radiation to that dissipated by convection, thus making it possible to predict the effect of altitude on the cooling of surfaces of different shapes, such as are found in stationary electrical apparatus, and (2) to give the results of experimental observations conducted on transformers (Fig. 1) under natural atmospheric conditions at different altitudes ranging from 305 m. (1000 ft.) to 3360 m. (11,000 ft.) These observed values are compared with theoretical calculations, making use of the established laws of the effect of barometric pressure on the principal modes of heat dissipation, namely, radiation, conduction and convection. From this a simple formula is developed, expressing the effect of altitude on the cooling of surfaces of various shapes.

GENERAL LAWS OF RADIATION, CONDUCTION AND CONVECTION OF HEAT

Radiation of Heat

The Stefan-Boltzman law that the radiation from a black body is proportional to the difference of the fourth powers of the absolute temperatures has withstood very rigid experimental investigations and can be considered as accurate. The Stefan-Boltzman law as applied to the radiation of heat from a body may be expressed

$$W_r = K\, e\, (T_2^4 - T_1^4) \tag{1}$$

where W_r = watts radiated per sq. cm. of surface.
K = an empirical constant.
e = relative emissivity which depends on the nature and color of the surface.
T_2 = absolute temperature of the radiating surface.
T_1 = absolute temperature of the room.

The exact value of K has not been definitely determined at present, but 5.7×10^{-12} (probably the most commonly accepted value) has been used in making calculations to check the experimental observations on surfaces of various shapes. To quote from Dr. Langmuir (Trans. A. I. E. E. Vol. xxxii, 1913 p. 309.)

"The radiation constant, 5.7, is subject to some uncertainty at present. For several years, the commonly accepted value was 5.32, which was the result obtained by Kurlbaum (*Wied. Am.* 65, 746, 1898). Recently, however, (1909), Fery obtained a value 6.3. Since then many investigators have redetermined this constant. Paschen and Gerlach (*Ann. d Physik*, Vol. 38, p. 30, 1912) obtained the value 5.9. Shakespeare (*Proc. of the Roy. Soc.*, Vol. 86A, p. 180, 1911) obtained 5.67. Within the next year or so the correct value of this constant will undoubtedly be determined. For the present, it would seem almost certain that the value 5.32 is too low, and that the value 5.7 must be fairly close to the true value."

Effect of Pressure, Color and Contour of Surface on Radiation

Since radiation of heat is purely a surface phenomenon, it is proportional only to the envelope of the surface and is independent of the pressure of gas. In other words, for a surface of an irregular contour it is the outer area, that is effective for radiation, and the rate of radiation is the same in vacuo as in a gas, all other conditions being the same.

For surfaces that are not black the heat radiated is always less than that of a perfect black body. The following tabulation, by Langmuir, taken from Table VII Trans. of the Am. Elec. Soc. Vol. 23-193, gives in part for various colored surfaces the relative emissivities e as percentage of that from a black body.

	Relative Emissivities e			
Temperature deg. cent. (room 27 deg.)	52	77	127	mean
Copper oxidized	77	70	76	74
Copper calorized	39	28	26	31
Silver (calculated)	1.7	1.9	2.1	1.9
Cast iron bright	17	20	23	20
Cast iron oxidized	50	67	64	60
Aluminum paint	67	60	45	57
Gold enamel	33	40	37	37
Monel metal bright	50	55	38	47
Monel metal oxidized	50	60	49	56

Again, if a surface is irregular such as we have in corrugated tanks for self-cooled transformers and the color is considerably different from a perfect black, the heat radiated from the cavities is greater than that radiated from a flat surface. This is due to the fact that besides the heat dissipated by direct radiation, additional heat is thrown out by reflection. However, the color

of the surfaces of the tanks used by the writer in the experimental observations (and also for practically all commercial transformers) was practically a lamp black, and e has been considered as unity, *i.e.*, no attempt has been made to make corrections for the color when making theoretical calculations. A small error may have been introduced due to this effect, but in general for surfaces of this color the error should be negligible.

Conduction of Heat

Since conduction of heat takes place by transference from one part of one body to another part of the same body without bodily transfer, this mode of heat transmission has very little, if any, effect on the change in temperature of stationary induction apparatus due to changes in barometric pressures. In other words, it is not necessary to consider it in this discussion. In general, however, for a steady flow of heat through a solid of uniform material the following law holds:

$$W = \frac{KA}{l} (T_2 - T_1) \tag{2}$$

Where W = watts of heat flow
K = coefficient of heat conductivity
A = area of cross section
l = length of conductor
$(T_2 - T_1)$ = temperature difference causing flow of heat.

Convection of Heat

Within the last four or five years Dr. Langmuir has done considerable work upon, and has developed a formula for, the convection of heat. His formula is based on the film theory, in which he assumes that the dissipation of heat takes place by first being conducted through a film of adhering gas, to the surrounding medium where it is carried away by convection air currents. The formula is expressed in the form

$$W_c = \frac{\phi_2 - \phi_1}{B} \tag{3}$$

Where W_c = Watts dissipated per sq. cm. surface
B = thickness of adhering film

and ϕ is a function of T (the absolute temperature) of the form

$$\phi = 1.93 \times 10^{-5} (1 + 0.00012\, T) \left[2/3\, T^{3/2} - 248\, T^{1/2} + 2760 \tan^{-1} \sqrt{\frac{T}{124}}\right]$$

From experimental observations, Dr. Langmuir found that for temperatures greater than 100 deg. cent. the value of B is 0.45 cm. Observations made throughout a wide range of high temperatures agree remarkably well with calculations using this empirical constant; but for low temperatures, of approximately 100 deg. cent. and less, he found it necessary to give B values greater than 0.45 cm. For example, for a 25 deg. cent. rise above 27 deg. room temperature, B had the value of 0.58 cm. and for temperature rises between 25 deg. cent. and 75 deg. cent. B ranged between 0.45 cm. and 0.58 cm. Since 0 deg. to 100 deg. cent. usually covers the temperature range found in self-cooled induction apparatus, this formula would not give correct results unless supplied with different values of B for different temperature values.

In 1817, Dulong and Petit announced the following law as a result of their experiments conducted over a rather limited range of temperatures.

> The velocity of the cooling due solely to the contact of a gas is proportional to the excess of temperature in degrees centigrade raised to the power 1.233.

This was later verified by Peclet.

Lorenz (*Ann. d. Physik*, Vol. 13, p. 582, 1881) by making certain assumptions derived for convection of heat from vertical plane surfaces the following formula:

$$W_c = 0.548 \sqrt[4]{\frac{c\, g\, K^3}{h\, H\, \theta_1}}\, \rho^{0.5}\, \theta^{1.25} \qquad (4)$$

where W_c = heat convection per sq. cm. of surface

c = specific heat of gas at constant pressure

K = its thermal conductivity

h = its viscosity

θ_1 = its average temperature in deg. cent.

ρ = its average density

g = gravitational constant

θ = difference in temperature of plane surface and of the gas at a great distance from the plane.

H = height of plane.

For 30 deg. cent. room temperature and for standard atmospheric pressure the above formula reduces to

$$W_c = 3.98 \times 10^{-4}\, H^{-\frac{1}{4}}\, \theta^{1.25} \qquad (5)$$

The results of observations conducted by the writer indicate that the loss vs. temperature rise follows a simple exponential law similar to Lorenz' formula (when H = approx. 9 cm.) throughout a range of temperatures from 0 deg. cent. to approximately 100 deg. cent. (tests were not made above 100 deg. cent.). This law also holds in plotting on logarithmic paper,

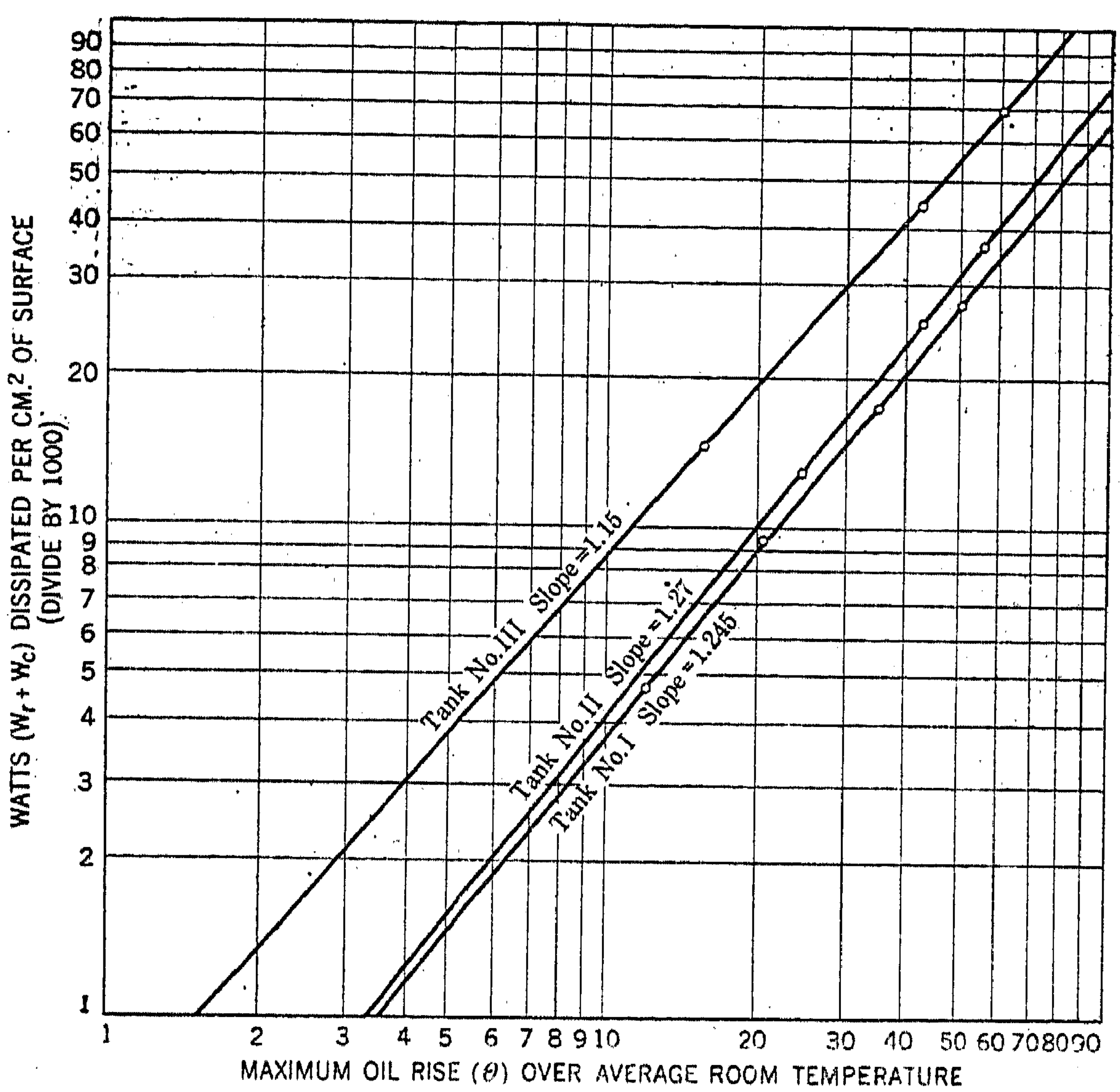


FIG. 2

the maximum oil rise of tanks with surfaces of various shapes against the loss dissipated per unit area of developed surface. Referring to Fig. 2 in which maximum oil rise is plotted on a logarithmic scale against loss per unit area of the developed surfaces of three tanks shown in Figs. 3 and 4, it will be noted that these points fall (for each tank) practically in a straight line. Providing the temperature gradients along the tank surfaces from top to bottom do not change for different maximum oil rises (and there is no reason why they should appreciably change) the equation of the line drawn through these points for any one tank, when supplied with the proper constant, (found

by trial), gives us the law of heat dissipation for that particular tank. This equation, however, includes here both radiation and convection.

Using an empirical formula for convection somewhat similar to equation (**5**), calculations indicate that tank No. 1 dissipated approximately 85 per cent of its loss by convection and 15 per cent by radiation; that tank No. II dissipated approximately 65 per cent of its loss by convection and 35 per cent by radiation; while tank No. III (plain), dissipated approximately 43.5 per cent of its loss by convection and 56.5 per cent by radiation.

The equation based on maximum oil rise for tank No. I should therefore be that, or nearly that, for the loss of heat by convection since a small percentage of its loss was dissipated by radiation. The slope of this line is 1.245 or

$$W = K\theta^{1.245} \tag{6}$$

where W = total watts dissipated per unit area of surface
K = constant (determined empirically)
θ = maximum oil rise above average room temperature

It will be noted that the above exponential value agrees remarkably well with that found empirically by Dulong and Petit (1.233) and also with that calculated by Lorenz (1.25). The writer finds that this formula holds very closely for maximum oil rise of tanks with various types of irregular surfaces, ranging from surfaces of simple corrugations to surfaces that are very complicated.

The equation of the line for tank No. II is

$$W = K\,\theta^{1.27} \tag{7}$$

and for tank No. III (plain surface)

$$W = K\,\theta^{1.15} \tag{8}$$

If we take from Fig. 6 (radiation curve) the temperature rise line based on 30 deg. or 35 deg. cent. room temperature and plot it on logarithmic paper, we obtain, between the limits of 10 deg. and 50 deg. rise, a line whose equation is approximately

$$W_r = K\,\theta^{1.12} \tag{9}$$

The exponent in equation (**8**) which involves approximately equal values of radiation and convection falls between the values 1.12 and 1.245, as would be expected. However, the temperature range from which equations (**7**) and (**8**) were based is not as wide

as that on which equation (**6**) is based and for this reason they are probably not as accurate. Refering to Fig. 2, it will be noted that equation (**6**) is based on four observed points. The lower one was obtained in Pittsfield only for the purpose of determining a more accurate exponential value, and therefore this test was not repeated at the higher altitudes. For temperatures within the range of the operation of stationary induction apparatus, the convection for vertical surface can no doubt be expressed within a reasonable accuracy by the simple equation

$$W_c = K\ \theta^{1.25} \qquad (\mathbf{10})$$

where W_c = watts dissipated per sq. cm. of surface (developed)
K = constant (found by trial to be 2.32×10^{-4} for tanks No. II and III and 2.04×10^{-4} for tank No. 1)
θ = temperature rise in deg. cent.

It is interesting to note that when we substitute 9.0 cm. for H in Lorenz's equation, it becomes

$W_c = 2.3 \times 10^{-4}\ \theta^{1.25}$ which is practically the same as equation (**10**).

Equation (**10**) is used later in comparing calculated values of loss by convection with the input loss less the calculated loss by radiation for three different styles of tanks. Also it is used in deriving a formula for expressing the effect of altitude on the cooling of surfaces of various shapes. It should be noted that it is not intended that this formula be applied for high temperatures where the formula $\frac{\phi_2 - \phi_1}{B}$ holds, but only for low temperatures of 100 deg. cent. and less.

Effect of Room Temperature on Dissipation of Heat

(*a*) *Radiation.* Referring to Fig. 6 it will be seen that room temperature has an appreciable effect on radiation. For example, for a 50 deg. rise the loss radiated in the presence of a 15 deg. cent. room temperature is 0.0354 watts per sq. cm., while in a 35 deg. cent. room temperature, the loss is 0.0427 watts per sq. cm.—a difference of 20 per cent, or 1 per cent per deg. variation in room temperature. For this reason an attempt was made to hold as nearly as possible the same room temperatures at the three different altitudes.* The room temperatures were the same at both Pittsfield and Leadville, while, due to encountering a period of very warm weather at

*See p. 621 for locations.

Boulder, it was necessary to hold a room temperature from one to six degrees higher than that held at the other two places.

(*b*) *Conduction*. Room temperature should have no effect.

(*c*) *Convection*. According to Dr. Langmuir's equation, $\frac{\phi_2 - \phi_1}{B}$, (plotted in Fig. 5) room temperature has very little effect on convection. No attempt has been made to add a room temperature correction factor in equation (**10**).

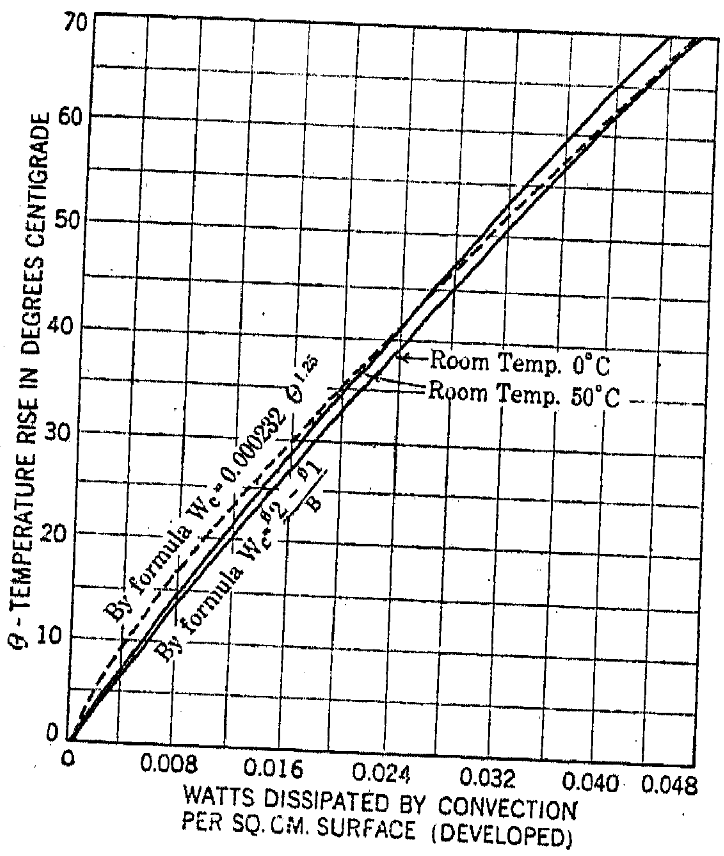


FIG. 5

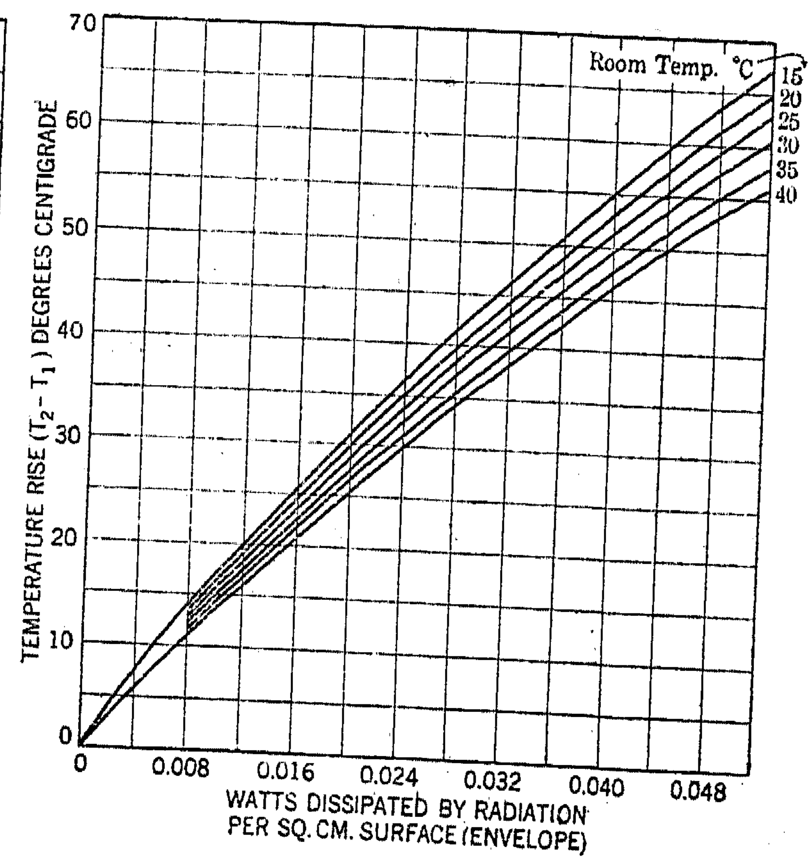


FIG. 6

EFFECT OF BAROMETRIC PRESSURE ON RADIATION CONDUCTION AND CONVECTION

(*a*) *Radiation*. Since radiation does not depend on the density of the surrounding air, changes in barometric pressure have no effect on it.

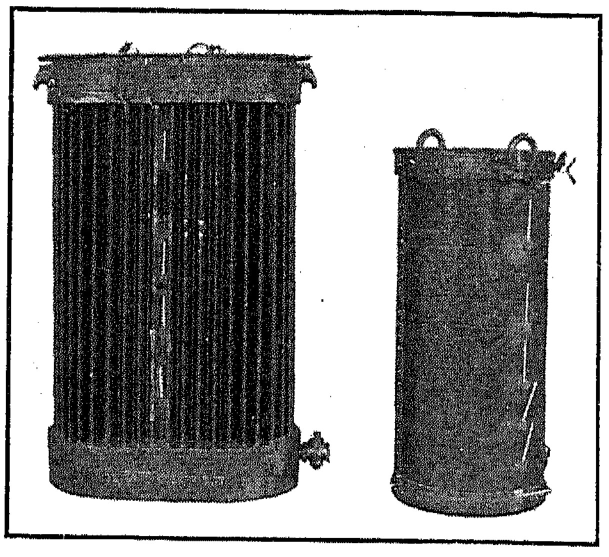
(*b*) *Conduction*. Changes in pressure do not affect conduction.

(*c*) *Convection*. In 1817 Dulong and Petit found that the velocity of cooling in a gas was proportional to the pressure raised to the power

0.45 for atmospheric air.
0.38 for hydrogen
0.517 for carbonic acid.
and 0.501 for olifiant gas.

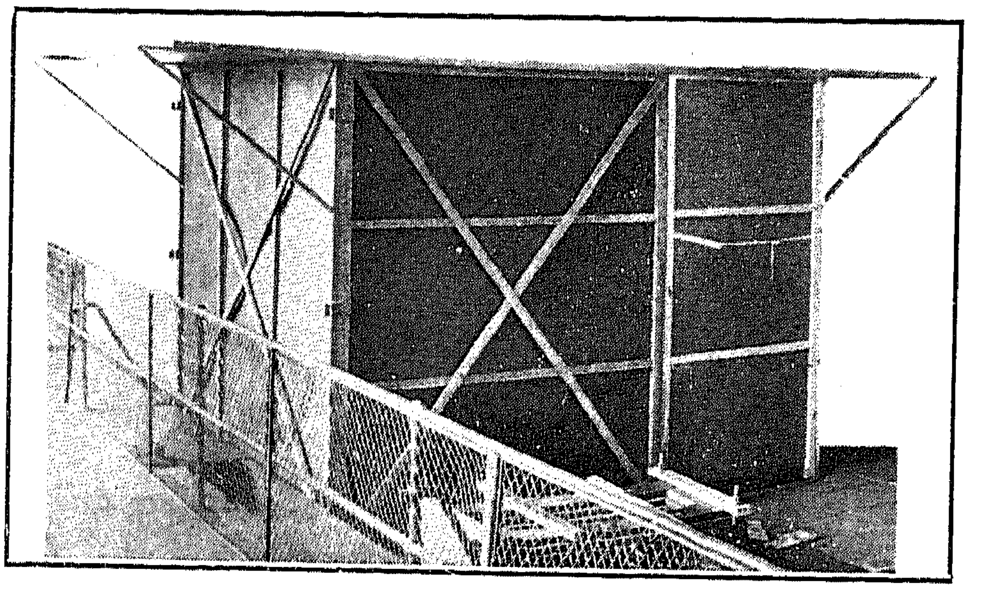
Messrs. Kennelly and Sanborn* in an investigation on "The

Proc. Am. Phil. Soc. Vol. liii, 1914.



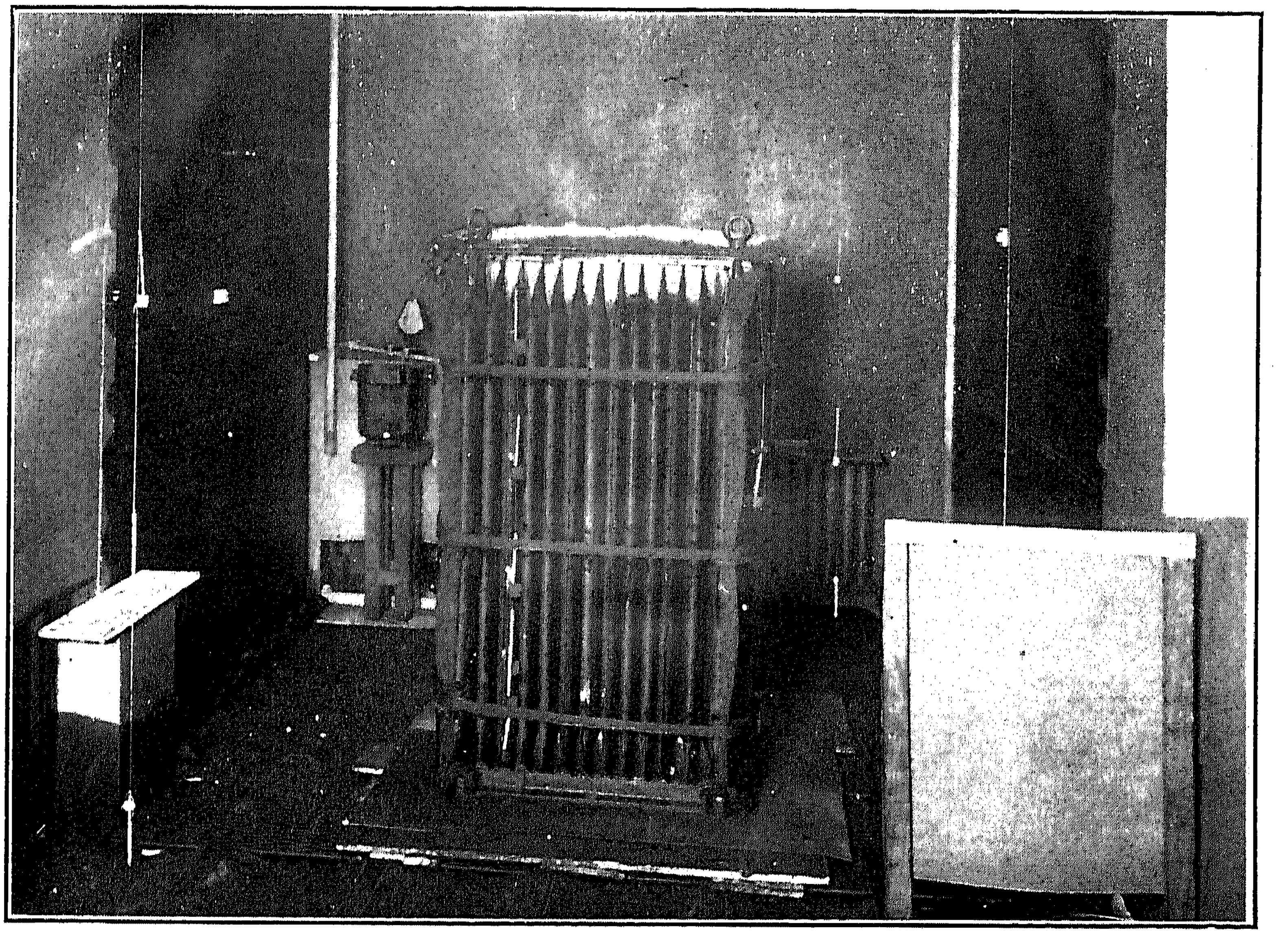
[MONTSINGER]

FIG. 3—CORRUGATED AND PLAIN TANKS USED FOR HEAT TESTS TO DETERMINE EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED TRANSFORMERS



[MONTSINGER]

FIG. 8—PRESSBOARD HOUSING USED FOR MAKING TESTS TO DETERMINE EFFECT OF BAROMETRIC PRESSURE ON TEMPERATURE RISE OF SELF-COOLED TRANSFORMERS



[MONTSINGER]

FIG. 4—SHOWING TANK NO. 1 IN HEAT RUN POSITION

Influence of Atmospheric Pressure upon the Forced Thermal Convection from Small Electrically Heated Platinum Wires," found that the linear convection is nearly proportional to the 0.5 power of the atmospheric pressure.

Compan found that for spheres 2 cm. in diameter, convection varies as the 0.45 power of the pressure. According to Lorenz's equation, convection varies as the 0.5 power of the pressure. In making calculation later on, the writer has used the value 0.5.

Effect of Position, Shape of Contour, and Height of Plane on Convection

Dr. Langmuir found that the convection was about 10 per cent more for the upper, and 50 per cent less for the under side of a horizontal plane than for a vertical plane. (Note: the covers for the tanks used in the experimental observations were insulated thermally from the horizontal surfaces so that practically no heat was lost by them, thus eliminating the necessity of making corrections when comparing input with calculated loss.)

Calculations indicate that the convection is practically the same for a plain surface, 130 cm. (51 in.) in height as for a surface having corrugations 8.9 cm. (3.5 in.) in depth, 5.72 cm. 2.25 in.) pitch and 130 cm. (51 in.) in height; but that the convection is approximately 15 per cent less for a surface having corrugations 22.8 cm. (9 in.) in depth, 6.03 cm. (2 3/8 in.) pitch and 140 cm. (55 in.) in height with upper and lower air spaces open for free circulation of air.

Again according to Lorenz's equation, convection varies inversely as the height of a vertical plane raised to the $\frac{1}{4}$ power ($H^{-1/4}$). Observation of tests made on vertical surfaces whose heights range from one or two meters to four or five meters indicate that the $\frac{1}{4}$ power is too large. In fact experience indicates that for simple corrugations and for heights ordinarily used for cooling of stationary induction apparatus, the effect of height is practically negligible. As an evidence that the $\frac{1}{4}$ power of the height is too great, if we substitute 130 cm. (corresponding to the heights of tanks used in the observations)for H in Lorenz's formula it becomes:

$$W_c = 1.18 \times 10^{-4}\ \theta^{1.25}$$

Referring to equation (**10**) it is seen that if we had used Lorenz's formula the calculated loss would have been only about 50 per cent of the loss actually found in the observation. But

as pointed out before for a height of 9 cm. the formula gives practically the same results as equation (**10**).

Method of Calculating Loss Dissipated from Tank Surface

For theoretical calculations, the temperature of the surfaces having corrugations was taken as an average of the temperature of the outside and inside bends. If the equations for radiation and for convection were not in exponential form, *i.e.*, if loss plotted against temperature rise were straight lines, it would only be necessary to determine the average temperature of the surface and this multiplied by the areas would give us the predicted losses by convection and by radiation. Again if we had an equation of the temperature gradient from the top to the bottom of the surface of each tank we could substitute in the general heat equations and integrate between limits, for calculating the losses. However, it would probably be a long and tedious task to derive an equation for the temperature gradient of the surface.

The most convenient method, (and the one used by the writer) is to use the process of summation, *i.e.*, to divide the area of the surface into sections for every few deg. rise, and calculate the loss for each section separately. The sum of the losses for the sections should be the total calculated loss. If the surface is divided into enough sections the error introduced is negligible.

Table I shows a comparison of the input loss (at Pittsfield) with calculated losses using the equations:

$$W_r = 5.7 \times 10^{-12} \, (T_2^4 - T_1^4) \qquad \text{for radiation}$$
$$W_c = K \, \theta^{1.25} \qquad \text{for convection}$$

and

$$W_c = \frac{\phi_2 - \phi_1}{0.45 \text{ cm.}} \qquad \text{for convection.}$$

The table shows, with the exception of the plain tank, that the equation $\frac{\phi_2 - \phi_1}{B}$ gives too high loss at lower temperatures, but that as the temperature increases the calculated and test values come close together, which indicates, as pointed out before, that B has a greater value than 0.45 cm. for low temperatures. For the plain tank the losses are so small, especially for test 7 that a few watts in observable errors would make a large error.

TABLE I.
COMPARISON OF CALCULATED LOSS WITH TESTS CONDUCTED AT PITTSFIELD.

Test	Max.* oil rise deg. cent.	†Ave. test watts input	Watts loss by convection: Tested (Input watts less calc. rad.)	Calculated by equations $W_c =$ $\frac{2.04\ \theta^{1.25}}{10^4}$	$\frac{2.32\ \theta^{1.25}}{10^4}$	$\frac{\phi_2 - \phi_1}{0.45 \text{ cm.}}$
		Tank No. I.				
1	21.1	1564.5	1268.0	1245.0	1413.0	1757.3
2	34.6	2910.0	2370.0	2380.0	2709.5	2985.0
3	50.9	4721.0	3811.0	3830.0	4461.0	4561.2
		Tank No. II.				
4	24.9	1550.	1023.4	......	1005.0	1266.
5	42.3	3114.0	2114.0	......	2041.0	2297.0
6	56.7	4500.0	3026.2	......	3129.0	3200.0
		Tank No. III.				
7	15.6	347.5	186.5	......	100.0	144.
8	41.9	1064.5	478.0	......	446.5	480.0
9	60.2	1657.5	704.5	......	722.3	735.1

*Based on the following average ambient temperatures:

For tests No.	1	2	3	4	5	6	7
Room (deg. cent)	30.0	30.1	32.0	30.0	32.0	32.0	29.9
Test No.	8	9					
Room (deg. cent.)	30.2	30.1					

†Ave. of volt × ampere and wattmeter readings.

THEORETICAL CALCULATION OF EFFECT OF PRESSURE ON COOLING

We now have sufficient data with which we should be able to predict fairly closely the increase in temperature of self-cooled stationary induction apparatus. Assuming that the loss dissipated by convection W_c varies as the 0.5 power of the barometric pressure, and as the 1.25 power of the temperature rise, and letting ρ equal the barometric pressure in mm. of mercury, the general equation for convection becomes

$$W_c = K\ \theta^{1.25}\ \rho^{0.5}$$

or

$$\theta^{1.25} = \frac{1}{K}\ \frac{W_c}{\rho^{0.5}}.$$

$$\theta = K_1 \frac{W_c{}^{0.8}}{\rho^{0.4}}$$ or compared with ρ at sea level

$$\theta = K_1\ W_c{}^{0.8} \left(\frac{760}{\rho}\right)^{0.4}$$

For a constant loss the temperature rise therefore varies inversely as the 0.4 power of the pressure.

Using the Smithsonian Institute's formula changed from English to metric system for altitude vs. barometric pressure, namely

$$\log_{10} \rho = \log_{10} 760 - \frac{A}{19.07377\,[1+0.00367\,(T-10) \text{ deg. cent.}]} \tag{11}$$

where

ρ = barometric pressure in mm. of mercury.
A = altitude in kilometers.
T = temperature in deg. cent. = 30 deg.

we obtain the following values:

when ρ =	760	711	664	621	570	542	507	474	mm.
or 1,000 A =	0	600	1200	1800	2400	3000	3600	4200	m.
% increase in θ =	0	2.72	5.6	8.75	11.4	14.60	17.52	20.9	
$\frac{\%\text{ increase in }\theta}{A}$ =	0	4.53	4.66	4.86	4.86	4.86	4.86	4.97	

The average of the above values is 4.8. With an average positive error (when A is greater than 1.2) of about 2.5 per cent, we may put

$$\phi_1 = 5\,A \tag{12}$$

where ϕ_1 is the percentage increase in temperature rise for a constant loss and A is the difference in altitude between lower and upper elevations expressed in kilometers (*i.e.*, for 1000 m. $A = 1$).

Effect of Pressure on Surface Dissipating Part of Loss by Radiation and Part by Convection

Equation (**12**) is applicable only for a surface dissipating all its loss by convection when naturally cooled. However, this condition seldom exists in commercial transformers.* The percentage of total loss by convection is probably from 40 to 45 per cent for a plain surface, whereas for surfaces with very complicated contours the loss by convection may approach more nearly 100 per cent. It follows, therefore, that the effect of altitude will be quite different for different types of surfaces—each one requiring special consideration.

This effect may be expressed in terms of the percentage of

*Natural draft transformers would come under this condition where the total RI^2 loss is carried away by natural circulation of air through ventilating ducts in the windings.

loss by convection to the total loss. For example, if only 50 per cent of the loss is by convection and the remaining by radiation (unaffected by pressure) the effect of pressure will be approximately one-half that expressed by equation (**12**). Letting ϕ_2 equal the percentage increase in temperature rise for surfaces having both radiation and convection, we have

$$\phi_2 = 5\,A \times \frac{\text{loss by convection}}{\text{total loss}}$$

or

$$\phi_2 = 5\,A \times \frac{W_c}{W_c + W_r} \qquad (\mathbf{13})$$

where W_c is the convection loss per unit area of developed surface and W_r is the radiation loss per unit area of envelope surface.

Since the ratio between W_c and $(W_c + W_r)$ does not remain quite the same when the altitude changes, equation (**13**) is not quite correct. For instance, when the apparatus is taken to a higher altitude the radiation increases while the convection may decrease. However, the error is small especially for surfaces with irregular contours such as corrugations, etc., where the greater part of the loss is by convection, and since it is a positive error, *i. e.*, it makes the estimated temperature rise slightly higher than it should be, it may be neglected for practical purposes. An attempt to correct for it would require an equation very cumbersome to handle.

If we assume a standard room temperature and a standard temperature rise, we can, for practical purposes, express W_c and W_r in terms of the developed and envelope surfaces reduced to equivalent values of loss per unit area. This makes it more convenient for practical application. For example, referring to Figs. 5 (either formula for convection) and 6 we find that for a 50 deg. rise above a 30 deg. room temperature the calculated watts dissipated per sq. cm. of surface are approximately in the ratio of 1.0 for convection to 1.3 for radiation.

We may therefore restate equation (**13**)

$$\phi_2 = 5\,AS \qquad (\mathbf{14})$$

where S = shape factor = $\dfrac{\text{developed surface of tank}}{(\text{dev.} + e\,1.3 \times \text{envelope})\ \text{surfaces.}}$

Derivation of General Equation for Effect of Barometric Pressure on Temperature Rise

We have seen that for temperature rises between 0 deg. and 75 deg. cent., the general equation of temperature rise vs. loss is $\theta = KW^n$ and that the equation of temperature rise vs. altitude is $\phi_2 = 5\,AS$. If we let θ = temperature rise at some high altitude, and

let W_0 = loss at room temperature θ_0 for given load conditions on the transformer

" W = loss at temperature rise θ

" $a = \dfrac{\text{copper loss}}{(\text{iron} + \text{copper})\text{ loss}}$

We may put $W_0 = W_0\,(1 - a) + a\,W_0$

Since iron loss is practically unaffected by temperature (see Trans. A. I.E.E., 1912, p. 2025, MacLaren) at temperature θ (for temperature coefficient of resistivity of copper of 0.00427 per cent per deg. cent.) the copper loss $= a\,W_0\left(\dfrac{234 + \theta_0 + \theta}{234 + \theta_0}\right)$

Then $$W = W_0\,(1 - a) + a\,W_0\left(\frac{234 + \theta_0 + \theta}{234 + \theta_0}\right)$$

$$= W_0\left(\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0}\right)$$

The temperature rise (say θ_x) for this loss at sea level will be

$$\theta_x = K\,W_0^n\left(\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0}\right)^n$$

If taken to a high altitude the temperature rise, with this loss, will be increased ϕ_2 per cent *i. e.*,

$$\theta = \theta_x + \frac{\phi_2}{100}\,\theta_x = \theta_x\left(1 + \frac{\phi_2}{100}\right)$$

$$= K\,W_0^n\left(1 + \frac{\phi_2}{100}\right)\left[\frac{234 + \theta_0 + \theta\,a}{234 + \theta_0}\right]^n$$

Let θ_s = temperature rise at the lower altitude for the given load conditions.

$$\theta_s = K\, W_s^n$$

$$= K\, W_0^n \left(\frac{234 + \theta_0 + a\,\theta_s}{234 + \theta_0} \right)$$

then
$$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right) \left[\frac{234 + \theta_0 + a\,\theta}{234 + \theta_0 + a\,\theta_s} \right]^n$$

Which may be written in the form

$$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right) \left[\frac{234 + \theta_0 + a\,\theta_s + a(\theta - \theta_s)}{234 + \theta_0 + a\,\theta_s} \right]^n$$

$$\text{Putting } \left(1 + \frac{\phi_2}{100}\right) = B$$

and
$$234 + \theta_0 + a\,\theta_s = D$$

$$\frac{\theta}{\theta_s} = B \left[1 + \frac{a\,(\theta - \theta_s)}{D} \right]^n$$

Expanding by the binomial theorem

$$\frac{\theta}{\theta_s} = B \left[1 + n\, \frac{a\,(\theta - \theta_s)}{D} + \frac{n\,(n-1)}{2} \cdot \frac{a\,(\theta - \theta_s)^2}{D^2} + . \right.$$

The terms after the second may be neglected without any appreciable error, then

$$\frac{\theta}{\theta_s} = B \left[\frac{D - n\,a\,\theta_s}{D - B\,n\,a\,\theta_s} \right]$$

$$= B \left[\frac{1}{1 - \dfrac{\dfrac{\phi_2}{100}\, n\,a\,\theta_s}{D - n\,a\,\theta_s}} \right]$$

or with an error of less than 1 per cent

$$\frac{\theta}{\theta_s} = B\left[1 + \frac{\frac{\phi_2}{100}\, n\, a\, \theta_s}{D - n\, a\, \theta_s}\right]$$

which reduces to

$$\frac{\theta}{\theta_s} = \left(1 + \frac{\phi_2}{100}\right)\left[1 + \frac{\frac{\phi_2}{100}\, n\, a\, \theta_s}{234 + \theta_0 + a\, \theta_s\,(1-n)}\right] \quad \textbf{(15)}$$

While equation (**15**) may be used for calculating the temperature rise for any altitude, it can be greatly simplified (without introducing any large errors) by assuming definite values of θ_0, θ_s, and n. Even though these values vary considerably in practise the effect on the final results is small and the error introduced by using average values is permissible.

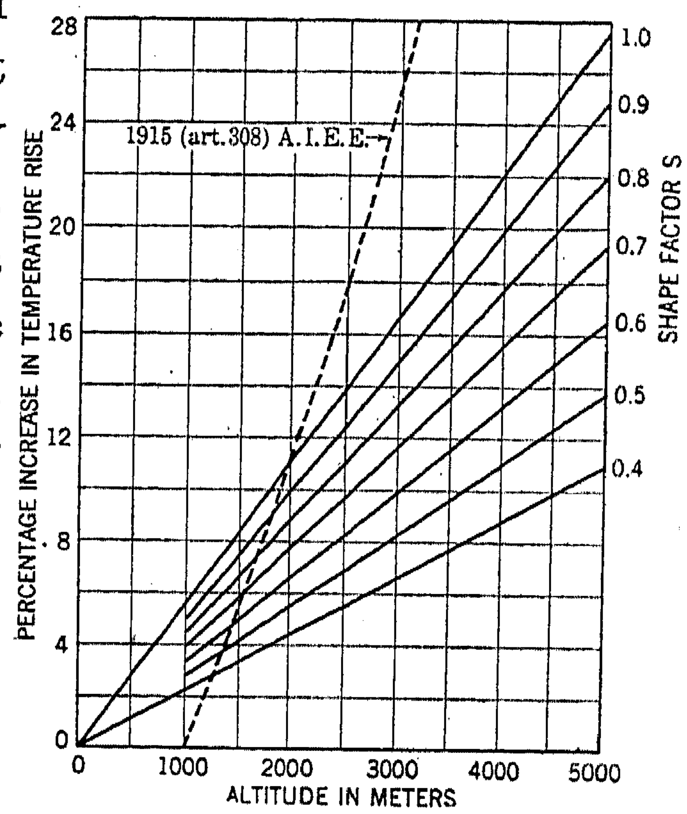


FIG. 7

Asumming a difference in altitude of 3000 m. (9840 ft.) or when $A = 3$ (in equation $\phi_2 = 5\ AS$) $S = 1$, $n = 0.8$, $\theta_0 = 30$ deg. cent. $\theta_s = 50$ deg. cent., and

$a = 0.0$, $\frac{\theta}{\theta_s} = 1.15$ or the new value of $\phi = 5.0\ AS$

$a = 0.5$, " $= 1.164$ " " " " " " $= 5.47\ AS$

$a = 1.0$, " $= 1.1753$ " " " " " " $= 5.85\ AS$

In other words, ϕ the percentage increase in temperature, ranges from 5 AS to 5.85 AS, depending on the ratio of copper loss to total (iron + copper) loss. Then we may put

$\phi = AS\,(5 + 0.85a)$ or with a maximum positive error of only 2.5 per cent when $a = 1$.

$$\phi = AS\,(5 + a) \quad \textbf{(16)}$$

Fig. 7 gives curves plotted from equation (**16**) where $a = 0.5$, and $e = 1$.

Table II shows a comparison between observed temperature rises and calculated temperature rises by equation (**16**) using the data shown in Tables III, IV and V giving complete data on observations conducted at Pittsfield, Boulder and at Leadville.

TABLE NO. II.

Test No.	Average surface rise deg. cent. at Pitts-field	Percentage temperature rise above tests at Pittsfield.					
		Tests at Boulder			Tests at Leadville		
		Predicted by equation (**16**)	Observed above		Predicted by equation (**16**)	Observed above	
			Average room	Idle tank		Average room	Idle tank
				Tank No. I.			
1	17.5	6.45	6.83	8.32	12.60	10.0	11.0
2	29.7	6.41	5.5	7.0	13.10	13.5	14.6
3	44.4	5.95	6.7	7.5	11.40	12.6	13.3
Mean values........		6.27	6.34	7.6	12.4	12.0	12.9
Mean value obtained by formula*..................					11.51		
				Tank No. II.			
4	15.8	5.00	0	0	9.95	6.06	7.40
5	31.1	5.10	3.3	1.85	10.00	8.75	9.50
6	44.4	4.90	1.95	1.78	9.85	8.65	9.95
Mean values........		5.0	1.42	1.27	9.93	7.82	8.95
Mean value obtained by formula*..................					9.3		
				Tank No. III.			
7	9.85	3.42	0	0	6.62	5.77	5.6
8	31.5	3.50	−3.34	− 3.34	6.92	3.82	4.05
9	48.3	3.35	−2.82	− 3.26	6.70	4.32	5.0
Mean values........		3.42	−2.08	− 2.2	6.74	4.6	4.88
Mean value obtained by formula*..................					6.12		

$*\phi = 4.86\,A\left(\frac{W_c}{W_c + W_r}\right)$. Note: Instead of using here a constant value (S) for $\left(\frac{W_c}{W_c + W_r}\right)$ for different temperature rises, the values for W_c and W_r are based upon actual watts dissipated as given by equations (**1**) and (**10**) for surface temperature rises shown in second column above. Since the values for W_c and W_r change in opposite directions for change in altitude, the calculations are made for the proper values at an altitude of 1525 m. (5000 ft.) above sea level.

TABLE NO. III.

RECORD OF TESTS ON TANK NO. I. (CORRUGATIONS 22.8 CM. IN DEPTH.)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
							Average maximum oil[3]								
								Rise above							
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Actual	Idle tank tank	Avg. room		Sea-level	Pitts-field			
							PITTSFIELD								
1	110	14.35	1565	1564	30.3	30.0	51.1	20.8	21.1	730	360	0	21	0.106	3-27-15
2	110	26.6	2913	2907	30.4	30.1	64.7	34.3	34.6	735	300	0	16	0.086	3-26-15
3	110	43.1	4728	4707	32.4	32.0	82.9	50.5	50.9	727	395	0	17	0.95	3-23-15
							BOULDER								
1	110	14.5	1583	1538	36.0	36.0	58.5	22.5	22.5	615	1880	1520	21	0.132	5-14-15
2	110	26.7	2925	2908	37.3	37.4	74.0	36.5	36.7	620	1810	1510	18	0.130	5-12-15
3	110	43.5	4773	4688	37.2	37.2	91.5	54.3	54.3	621	1795	1400	20	0.140	5-10-15
							LEADVILLE								
1	110	14.35	1565	1564	29.9	29.8	53.0	23.2	23.1	523	3320	2960	25	0.122	7-24-15
2	110	26.4	2891	2897	30.0	30.0	69.3	39.3	39.3	519	3390	3090	20	0.099	7-23-15
3	110	43.1	4728	4727	30.9	30.9	88.2	57.3	57.3	537	3080	2685	22	0.106	7-22-15

(1) Less instrument losses.
(2) Average of 4 thermometers.
(3) Average of 3 thermometers.

TABLE NO. IV.

RECORD OF TESTS ON TANK NO. II. (CORRUGATIONS 8.9 CM. IN DEPTH.)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Average maximum oil[3] Actual	Rise above Idle tank	Rise above Avg. room		Sea-level	Pittsfield			
							PITTSFIELD								
4	110	14.25	1554	1547	30.5	30.1	54.9	24.4	24.8	727	395	0	16	0.081	3–19–15
5	110	28.4	3111	3117	32.3	32.0	74.3	42.0	42.3	728	382	0	14	0.081	3–18–15
6	110	41.0	4493	4507	32.4	32.0	88.7	56.3	56.7	723	443	0	14.5	0.078	3–16–15
							BOULDER								
4	110	14.25	1554	1556	31.5	31.1	55.9	24.4	24.8	616	1890	1495	34	0.176	5–20–15
5	110	28.8	3163	3117	36.4	35.5	79.2	42.8	43.7	613	1910	1528	29	0.188	5–18–15
6	110	41.5	4552	4573	38.8	38.3	96.1	57.3	57.8	613	1910	1467	22.5	0.162	5–17–15
							LEADVILLE								
4	110	14.1	1548	1547	30.2	30.0	56.4	26.2	26.4	520	3370	2975	21	0.110	7–27–15
5	110	28.4	3111	3117	31.8	32.0	78.0	46.2	46.0	519	3390	3008	24	0.130	7–26–15
6	110	41.3	4517	4517	31.7	32.0	93.6	61.9	61.6	519	3390	2947	24	0.116	7–25–15

(1) Less instrument losses.
(2) Average of four thermometers.
(3) Average of three thermometers.

TABLE NO. V.

RECORD OF TESTS ON TANK NO. III. (PLAIN)

Test	Volts	Amperes	Watts[1] observed by		Temperature in deg. cent.					Observed barometric pressure in mm. Hg.	Calculated altitude in meters above		Humidity of air in % of saturation	Grains of moisture per litre of air	Date of test
							Average maximum oil[3]								
								Rise above							
			Volts × amp.	Watt-meter	Idle tank	Avg.[2] room	Actual	Idle tank tank	Avg. room		Sea-level	Pittsfield			
							PITTSFIELD								
7	110	3.28	348	347	29.4	29.9	45.5	16.1	15.6	732	333	0	18	0.092	3- 2-15
8	110	9.78	1063	1066	30.1	30.2	72.1	42.0	41.9	743	201	0	17	0.092	3- 4-15
9	110	15.2	1658	1657	30.4	30.1	90.3	59.9	60.2	736	285	0	18	0.092	3- 6-15
							BOULDER								
7	110	3.23	354	342	33.6	33.6	49.0	15.4	15.4	616	1890	1557	40	0.240	5-25-15
8	110	9.87	1073	1067	33.9	33.9	74.4	40.5	40.5	613	1910	1609	24	0.148	5-23-15
9	110	15.6	1703	1637	33.7	33.2	91.7	58.0	58.5	619	1825	1540	32	0.190	5-22-15
							LEADVILLE								
7	110	3.26	346	313	29.5	30.0	46.5	17.0	16.5	519	3390	3057	18	0.105	7-29-15
8	110	3.78	1063	1066	29.8	30.0	73.5	43.7	43.5	519	3390	3189	19	0.113	7-28-15
9	110	15.2	1658	1667	30.0	30.1	92.9	62.9	62.8	520	3370	3085	19	0.105	7-27-15

(1) Less instrument losses.

(2) Average of four thermometers.

(3) Average of three thermometers.

An inspection of Table II shows that the calculated and observed temperature rises for all tests on tank No. I, which is the most important of the three, (because the effect is greatest) agree very well. Also there is only a slight difference, the observed being lower than the calculated values, for the Leadville tests on tanks No. II and III. Why the observed and calculated values for the Boulder tests on Tanks No. II and III do not agree any better is not clearly understood. This difference may be partly explained by the fact that different instruments were used at Boulder than at Pittsfield. A small error in watts would be expected to be more apparent for the smaller tanks where the loss is small. Another and probably better reason for this difference is that the room temperatures were from three to six degrees higher at Boulder than at Pittsfield, which as seen before, has the effect of increasing the tank's effectiveness for radiation. The difference is largest for the plain tank where radiation plays the more prominent part. Also the humidity of the air at the former place was somewhat higher, but in general this has been shown to have very little effect. (See TRANS. A. I. E. E. 1913, Vol. XXXII, Part I, p. 235. Frank and Dwyer)

EXPERIMENTAL OBSERVATIONS

Observations were made under exactly the same conditions, with the above exceptions, at

Pittsfield, Mass.	approx.	305 m.	(1000 ft.)	above sea level
Boulder, Colo. *	"	1830 m.	(6000 ft.)	" " "
Leadville, Colo.	"	3360 m.	(11,000 ft.)	" " "

The writer had charge of the observations at Pittsfield and at Leadville. This eliminates the personal element which is usually important in any test on heating.

The housing (Fig 8) consisted of pressboard walls made up into sections so it could be easily assembled and disassembled. A view of the arrangements on the inside of the housing is shown in Fig. 4. The room temperature was controlled by means of sliding covers. In a few instances when the supplied loss was small, in order to keep the room temperature from falling below the chosen value, it was necessary to use a small electric heater.

Two 40.6-cm. (16-in.) desk fans were operated in a vertical

*It is desired here to acknowledge indebtedness to Prof. H. S. Evans, of the University of Colorado, who had charge of and conducted the observation at Boulder at the expense of the University Eng. Dept. Also the writer wishes to ackdowledge the excellent work done by Messrs. C. D. Fawcett and T. M. Victory in carrying on the observations at Boulder and at Leadville.

position in opposite corners of the room, with pressboard screens placed between the fans and the tank to prevent breezes from striking the surface of the tank. Tests made in this manner at different outside temperatures showed that under all conditions the difference in air temperature (approx. 90 cm. from tank surface) on level with the top and bottom of tank did not in any case exceed 2 deg. cent., whereas without the fans sometimes as much as 6 to 8 deg. cent. difference was observed. The room temperature used as a base was taken as the average of the four thermometers placed on a level with the center of the tank, in each corner of the room as shown in Fig. 4. In addition to the room temperature being used as the base, the temperature of a small lighting size transformer tank, filled with oil, set with its center on a level with the center of the tank under test, was also used. This was subjected less to quick changes in the outside air, than was the internal room temperature. The percentage of humidity of the air, during all tests, was determined by means of wet and dry mercury bulb thermometers. The barometric pressure was observed with a mercurial barometer.

Tanks. The dimensions of the three tanks used are given in Fig. 1.

It will be noted from the illustrations that the covers for the three tanks are insulated thermally from the tanks proper. Also for tank No. 1 the two plain sides were covered each with two thicknesses of 2.54-cm. (1-in.) hair felt, so as to make the loss by convection a maximum. However, in order to determine the amount of heat passing out through these blanketed sides, the blanketing material was covered with a sheet iron casing of black color. By observing the temperature of this casing and also of the covers it was possible to determine the amount of heat lost by these insulated areas.

Tank No.	Run No.	Estimated loss by blanketed areas in percentage of of input loss
I	1	2.5
	2	2.2
	3	2.9
II	4	1.32
	5	0.75
	6	0.70
III	7	1.5
	8	1.8
	9	1.9

The foregoing tabulation gives the estimated loss by these blanketed areas in percentage of input loss on each tank for the tests conducted at Pittsfield.

We can therefore neglect these surfaces in giving the ratio of developed (effective for convection) to envelope (effective for radiation) surfaces. However, in making calculations of dissipated heat, these blanketed areas have been considered.

The developed surfaces effective for convection therefore were as follows:

TANK No. I. (24 corr. 22.9 cm. in depth)		
Corr.—$24 \times 48.5 \times 141.5$	165,000 sq. cm.	(25,600 sq. in.)
Space above corr. not blanketed	3,225 "	(500 ")
	168,225 "	(26,100 ")
TANK No. II. (43 corr. 8.9 cm. in depth.)		
Corr.—$43 \times 19.8 \times 130$	111,000 sq. cm.	(17,200 sq. in.)
Plain bands at top and bottom $40.6\ (73.8 + \pi \times 63)$	10,980 "	(1,700 ")
	121,980 "	(18,900 ")
TANK No. III. (Plain sides)		
$59 \times \pi \times 130$	24,200 "	(3,750 ")

The envelope surfaces (not blanketed) effective for radiation were:

TANK No. I. $24 \times 6.02 \times 159$	23,000 sq. cm.	(3,560 sq. in.)
TANK No. II. $167.5\ (4 \times 18.4 + \pi \times 63)$	45,500 "	(70,600 ")
TANK No. III. $59 \times \pi \times 130$	24,200 "	(3,750 ")

The values of S as defined in equation (**14**) for the above tanks are:

Tank No.	S
I	0.85
II	0.67
III	0.435

Method of Loading. Each tank was fitted with tubes wound (non-inductively) with resistance wires of zero temperature coefficient, and so arranged that by connecting in parallel various combinations proper losses were supplied, at 110 volts pressure, to give three maximum oil rises ranging from about 20 to 60 deg. cent. These tubes were so grouped that for each test the loss was uniformly distributed over the tank. By means of a diagrammatic record the same grouping was used at Pittsfield, at Boulder and at Leadville. The tubes were supplied at Pittsfield and at Boulder with current from an a-c. generator, and from an a-c. circuit of the Colorado Power Company at Leadville. The regulation was within one per

cent under all conditions. In fact, at Leadville the regulation was considerably better than one per cent.

The instruments consisted of

One 150-volt voltmeter

One 5-ampere ammeter

One 600-watt, 15-ampere, 150-volt wattmeter

One 10:1 ratio current transformer.

The wattmeter was used to obtain a check on the input losses as found by the volt-ammeter method. (volts × amperes). The same instruments were used at both Pittsfield and Leadville. At Boulder the meters were furnished by the University of Colorado. All the thermometers were of the mercury bulb type and only those reading accurately within ½ deg. cent. by calibration were used. The four used for room read in $\frac{1}{5}$ deg. divisions. The three used for the maximum (top) oil read in ½ deg. divisions.

In order to obtain the temperature gradient along the surface of the tanks (for checking input against dissipated losses), thermometers were placed at short intervals from top to bottom on both outside and inside bend of corrugations. Small felt pads and putty were placed over the bulbs to protect them from the influence of the room. At Pittsfield thermocouples were welded to the tank surface adjoining five of these thermometer bulbs to obtain a check on the temperatures. The thermocouples and thermometers read together, in almost all cases, within 1 deg. cent., showing that the felt pads were not causing hot spots from a blanketing effect.

For each test the run was continued at least 8 or 10 and in some cases 15 to 20 hours after conditions became constant, and an average of these readings (observed hourly) was taken as the final value.

CONCLUSIONS

The present A. I. E. E. recommendation (§308) reads as follows:

Altitude. Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 ft.). For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. See Para. 267. It is recommended that when a machine is intended for service at

altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, until more nearly accurate information is available, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters. Water-cooled oil transformers are exempt from this reduction.

COMPARISON OF A. I. E. E. RECOMMENDATIONS WITH $\phi = AS\,(5 + a)$

	Per cent increase in temperature rise above temperature rise at sea level.				
Altitude above sea level — Meters.	1000	2000	3000	4000	5000
Altitude above sea level — Feet....	3280	6560	9840	13,120	16,440
A. I. E. E. (§308)......	0	11.1	25.0	42.8	66.8
Shape factor S	$\phi = 5.5\,AS$				
1.0	5.5	11.0	16.5	22.0	27.5
0.75	4.12	8.25	12.4	16.5	20.6
0.435	2.39	4.78	7.18	9.57	12.0

The above indicates that for equal iron and copper losses the present A. I. E. E. recommendations are for a difference of altitude of 3000 m. (9840 ft.), about 1.5 times too high for a surface with no radiation; about two times too high, for a surface dissipating 75 per cent of its loss by convection and 25 per cent by radiation (which ratio corresponds somewhat more nearly to surfaces of simple corrugations); and about 3.5 times too high for a plain surface ($S = 0.435$). For altitude differences greater than 3000 m. the error is larger, while for altitude differences less than 3000 m. the error is less.

Recommendations. It is recommended that for self-cooled (oil-immersed and natural draft) transformer, either the formula $\phi = AS\,(5 + a)$ or the one simplified and shown below be adopted and that no correction be made when $A = 1$ or less. If we assume that $e = 1$ and that the ratio of copper to iron loss is 3:2 respectively and divide the numerator and denominator of the expression for the shape factor through by "developed surface," we have

$$\phi = \frac{A\,(5 + 0.6)}{1 + 1.3\,\dfrac{\text{envelope surf.}}{\text{developed surf.}}}$$

or

$$\phi = \frac{5.6\,A}{1 + 1.3\,R} \tag{17}$$

where R = area of envelope cooling surface divided by area of developed cooling surface.

NOTE: In practise R varies from 1.0 (plain surface) to approximately 0.125 (complicated surface). For natural draft transformers dissipating all heat by convection $R = 0$.

Example. Let it be required to determine the temperature rise that a transformer in tank No. II (corrugations 8.9 cm. in depth) giving a 45 deg. cent. rise at sea level will attain when taken to an elevation of 3000 m. (9840 ft.).

We have $A = 3$

and
$$R = \frac{46080}{121980}$$
$$= 0.378$$

Then

$$\phi = \frac{5.6 \times 3}{1 + 1.3 \times 0.378}$$
$$= 12.8 \text{ per cent*}$$

or temperature rise at 3000 m. above sea level will be 45 deg. $+ \left(\frac{12.8}{100}\right)$ 45 deg. = 50.7 deg. cent.

If it is desired to make correction in the opposite direction, *i.e.*, one of reduction instead of one of addition, and if we let ϕ_r = percentage reduction in temperature rise at the high altitude

$$\phi_r = \frac{100\ \phi}{100 + \phi} \tag{18}$$
$$= 11.44 \text{ per cent or}$$

temperature rise at sea level will be, 50.7 deg. $- \left(\frac{11.44}{100}\right)$ 50.7 deg. = 45 deg. cent.

* It should be noted that this percentage increase applies to the max. oil temperature rise rather than to the average temperature rise of the windings, which in some cases differs considerably from the oil. Since the difference between the winding and max. oil temperatures should be about the same at all altitudes, the same number of degrees correction should be made for the windings as for the oil.

Discussion on "Effect of Barometric Pressure on Temperature Rise of Self-Cooled Stationary Induction Apparatus" (Montsinger), Cleveland, Ohio, June 27, 1916.

R. W. Sorensen: Mr. Montsinger in presenting this most excellent treatise has placed before us a second set of data* for the purpose of enabling our Standards Committee to construct an accurate ruling, whereby the effect of altitude upon the heating of electrical apparatus may be determined.

In classing this as a second set of data, I have used that given by Frank and Dwyer as the first set, because in both these instances the test data used in arriving at the conclusions given, were derived from tests made largely at the same geographical locations; and also because the working up of these data was accomplished by the use of the same formulas of Dr. Langmuir's and others, as may be seen from a comparison of the paper by Mr. Montsinger with that previously published by Messrs. Frank and Dwyer.

Unfortunately, the results of the two investigations do not check as closely as would be desirable, as will be seen by the curves of Fig. 2. Also the curves obtained from these results do not approximate the A. I. E. E. rules (§308), as has already been pointed out by Mr. Montsinger in his paper.

For our assistance, therefore, I should like to present data of a series of heat run tests that I made on two oil-insulated self-cooled transformers. These tests were made at Schenectady, New York, Pittsfield, Mass., Grand Junction, Colorado, and Leadville, Colorado, with altitudes of 75, 345, 1525 and 3190 meters respectively, as indicated by barometer readings at the time and place of test.

The transformers used for the tests were rated 60-cycle, 125-kv-a., 11,000 volts to 2300 volts, and contained approximately 1300 pounds of active material (copper and iron). They were inclosed in corrugated sheet steel tanks with a cast iron base and wrought iron straps at the top for holding the corrugations in place. Each tank was about 5½ feet high, and occupied a floor space of approximately two feet by three feet in area.

The tests which I made, while not conducted in a special portable room, as were those of Mr. Montsinger, were conducted with special care as to uniformity of ventilation conditions in the large rooms of the factories and power plants where the tests were made. Observations were made of humidity at each place of test, and agreement of conditions in this respect found to be such that no corrections for differences of humidity were necessary.

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*Frank and Dwyer "The Temperature Rise of Stationary Induction Apparatus as Influenced by the Effects of Temperature, Barometric Pressure and Humidity of the Cooling Mediums," page 235, A. I. E. E. Transactions, Vol. XXXII.

All heat runs were conducted by the standard motor generator method of loading two transformers for heat run, and readings of currents, volts and watts input to each transformer were made, to insure the accuracy of the knowledge of the watts to be dissipated, regardless of variations in wave form of voltage supply, etc.

The results of these tests were as follows:

Place.	Actual watts loss.	Rise in oil deg. cent.	Rise in oil deg. cent. reduced to same loss 4820 watts
Schenectady..................	4820	36.0	36.0
Pittsfield....................	4820	37.5	37.5
Grand Junction...............	3965	32.5	38.9
Leadville.....................	4570	39.6	41.8

From these results there is plotted on Fig. 1, curve *A* showing the probable change in temperature rise at various altitudes for a constant loss of 4820 watts in the transformers. The points located on the figure show the actual conditions as found by the tests made. Considering curve *A* on Fig. 1 as indicative of the true condition, it has been replotted as curve *D*, Fig. 2. Assuming, however, the test at Schenectady (36 deg. cent. rise) as correct and using this as a base, a greater influence of altitude is shown when the temperature rise of Leadville is compared with it and there results curve *E*, which has been plotted in Fig. 2, because it shows this condition, and also because it gives a possible conservative rule easy to follow, its slope being such as to show $\frac{1}{2}$ of 1 per cent increase in temperature rise for each 100 meters altitude.

Applying to results of tests on these transformers Mr. Montsinger's method of analysis, we find the tanks were similar to those of Fig. 1. tank No. 2 in his paper, except in that the corrugations were spaced a greater distance apart. The tank dimensions were 65 inches (165 cm.) high over all, and had thirty-two $3\frac{1}{2}$ in. (8.9 cm.) corrugations each, with a pitch of three inches (7.62 cm.) per corrugation, making the developed surface as follows:

*Corrugations	$4 \times 66.5 \times 55$	14,630 sq.in. (94,500 sq.cm.)
Upper plain band	$4(29+24.75'')$	426 " " (2750 " ")
Lower plain band	$6(29+24.75'')$	640 " " (4130 " ")
Envelope surface	$= 65(29-24.75'') =$	6950 sq. in. (44,800 sq. cm.)
		15,696 sq. in. (101,330 sq. cm.)

Therefore:

$$(\text{Leadville}) = \frac{5.6 \times 3.19}{1 + 1.3\,(6950/15696)} = 11.3 \text{ per cent.}$$

*66.5 inches is the developed length of each one of four sheets of steel, making up the corrugated walls of the tank.

At first sight this result does not appear to check very closely the tests made upon the 125-kv-a. transformers as will be seen by comparing curves *D* and *E* with curve *C* of Fig. 2. A very careful consideration, however, of the data obtained from the tests on the transformers shows a possibility of a very close agreement between these and the results obtained by Mr. Montsinger.

At the time the tests were made on these transformers, it was feared that in moving about from place to place it would not be possible to have a fixed set of conditions at each place, and consequently a number of heat runs at different loads and voltages were made at Pittsfield (altitude 345 meters). These many tests, carefully made and checked with each other make them

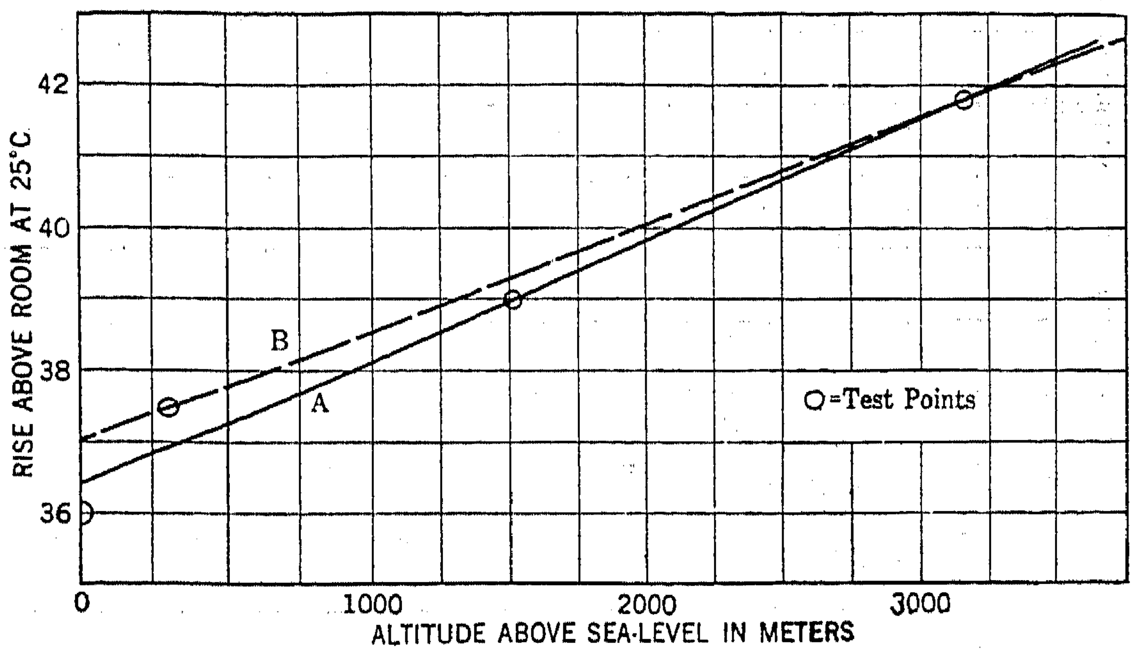


FIG. 1—TEMPERATURE RISE OF 125-KW., 11000-2300-VOLT TRANSFORMERS DUE TO CHANGE IN ALTITUDE.

CURVE A—PROBABLE TEMPERATURE RISE CURVE FOR 125-KV-A. TRANSFORMERS AS OBTAINED FROM ALL FOUR TEST POINTS

CURVE B—PROBABLE TEMPERATURE RISE CURVE FOR 125-KV-A. TRANSFORMERS AS OBTAINED WITH TESTS AT PITTSFIELD AS BASIC

worthy of consideration in establishing a basic "rise of temperature."

With the temperature rise for a loss of 4820 watts determined at Pittsfield as a base, the possible temperature increase curve may be drawn through the Pittsfield and Leadville points as of curve *B*, Fig. 1. This curve shows a rise of 37.5 deg. at sea level, which means an increase in temperature rise of approximately 1.2 per cent at Pittsfield over that of Schenectady.

By Mr. Montsinger's formula:

$$\phi \text{ (Pittsfield)} = \frac{5.6 \times 0.345}{1 - 1.3\ (6950/15696)} = 1.22 \text{ per cent.}$$

With probable rise of 37.05 deg. cent. at sea level (Schenectady) and a rise of 41.8 deg. cent, at Leadville, there is an increase in temperature rise at Leadville over that at Schenectady (sea level) of 4.75 deg. cent. or 12.8 per cent, which compares favor-

ably with the increase of 11.3 per cent as obtained by the use of Mr. Montsinger's equation (17), and we can draw curve K as a possible curve for the 125-kv-a. transformers as of the tests made in June, 1910.

It is quite probable, therefore, that the curve E is somewhat high, and that practically all self-cooled oil-insulated transformers would give results within the range limited by curves C and D.

These facts show very clearly that Mr. Montsinger's paper

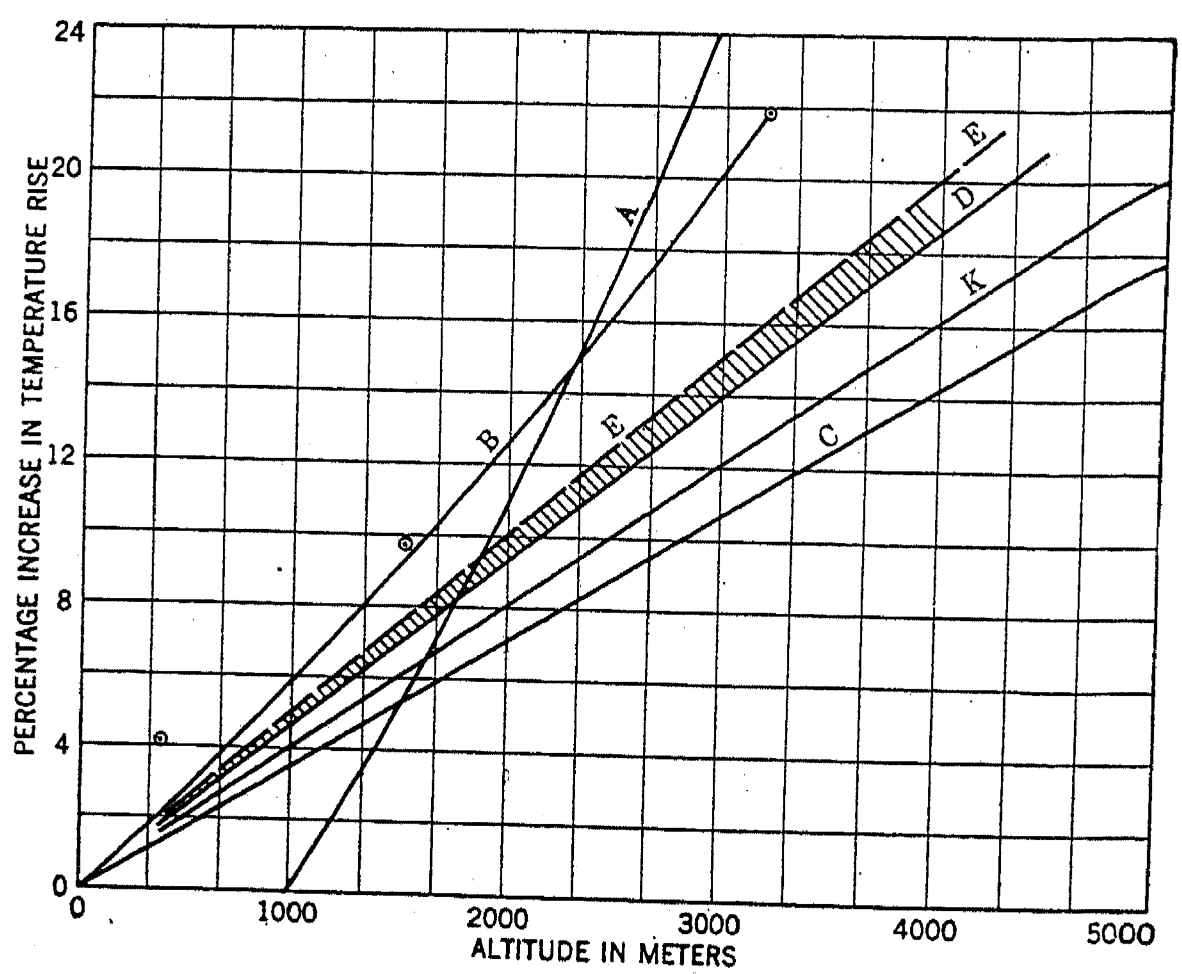


FIG. 2

CURVE A—1915 (ART. 308) A. I. E. E. RULES

CURVE B—FROM TABLE II D, FRANK & DWYER, PAGE 254, A. I. E. E. TRANSACTIONS, VOL. XXXII

CURVE C—VALUES FOR 125-KV-A. TRANSFORMERS OBTAINED BY EQUATION (17), MONTSINGER, A. I. E. E. PROCEEDINGS, APRIL, 1916.

CURVE D—VALUES FOR 125-KV-A. TRANSFORMERS OBTAINED FROM TESTS, AS OF CURVE A, FIG. 1

CURVE E—FOR SUGGESTED RULE OF ONE-HALF OF ONE PER CENT INCREASE FOR EACH 100 METERS ALTITUDE

CURVE K—VALUES FOR 125-KV-A. TRANSFORMERS WITH THE TESTS AT PITTSFIELD BASIC, AS OF CURVE B, FIG. 1

has advanced us materially in the solution of this problem, but it seems hardly advisable for the following reasons, to adopt the recommendation as given in his paper whereby his equation (17) is to be used. His Fig. 7 shows that for a shape factor of 0.9, a curve that practically coincides with curve E, Fig. 2. Also it is possible that there may be conditions governing the oil circulation of actual transformers different from those of the experimental apparatus used by Mr. Montsinger in obtaining his results, so that some curve between curves E and C of Fig. 2

would more nearly approach the average results of a large number of transformers of various designs.

I would recommend, therefore, that, until further information can be obtained, an increase of temperature of one-half per cent be allowed for each 100 meters altitude, as this will be more nearly correct than the present rule and will at the same time allow ample margin for safety, as the $\frac{1}{2}$ per cent is undoubtedly somewhat in excess of the necessary allowance.

A. I. E. E. rule § 308 would then read the same as at present with the exception of the next to the last sentence which would read about as follows:

It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 feet) the rise in temperature shall be determined, until more nearly accurate information is available, by adding to the rise at sea level one-half per cent for each 100 meters (330 ft.) of altitude.

Alexander Gray: If duplicate machines are tested by different men for temperature rise the results will differ. Accurate measurement of temperature is not easy and any small error in reading will give results from which it will be impossible to deduce any law of cooling.

I once started some work on the heat dissipation from vertical surfaces but without great success. The apparatus consisted of a wooden cylinder on which strip copper was wound and the surface temperatures were determined by resistance measurements. By juggling coefficients I finally obtained a radiation coefficient of about 0.75 and a law of convection that agreed accurately with Lorenz law. I am inclined to think, however, that I was looking for such a law and adjusted the radiation coefficient to suit and, having come to that conclusion, I decided thereafter to leave the subject to the physicist.

There has recently been developed at the Bureau of Standards an instrument by means of which the actual radiation from a surface may be determined so that the field looks promising for those interested in heating problems.

It is of interest to note that in the report presented by the Transmission Committee, the Trinidad Company states that, at high altitudes, transformers ran ten per cent hotter than normal while rotating machines ran only five per cent hotter and yet the rotating machine is that in which nearly all the heat is dissipated by convection.

When heat is dissipated by means of air blown over a surface a reduction of the density of the air causes an increase in its temperature but this does not necessarily mean that the surface temperature is increased by the same amount. There is a large temperature gradient between the surface and the air about which we know very little and because of this I do not believe that we are in a position to make any recommendation as to the correction to be made for barometric pressure.

Experimental data such as those contained in Mr. Montsinger's

paper add to our knowledge of a very difficult subject but I believe much more of such work is necessary before we are in a position to make more than a recommendation as to the correction for barometric pressure.

V. M. Montsinger: In reference to Prof. Sorensen's discussion, although the curve which he considers most reliable checks very closely the results I obtained, he does not recommend a correction in accordance with the formula, but recommends one correction for all transformers, which is slightly less than the maximum correction by the formula. He states that it will take care of all the cases which come up. That is true. My point is, however, and I have tried to emphasize it, if we have only one correction factor for all types and have one transformer for which the correction is only about 7 per cent as is the case for a tank having plain surfaces, for a difference of 10,000 ft. in elevation, it is not necessary to design this transformer with a margin of 15 or 20 per cent. I believe that it is advisable to adopt some formula that will take care of this difference, because if we attempt to continue to make one correction for all types of apparatus, especially for stationary and moving types, the problem will still remain in a very unsettled condition.

Regarding Prof. Sorensen's statement that the conditions may not have been the same, where I heated the tanks by means of resistance tubes, as are the conditions in an actual transformer. This may be true if we considered only the windings of the transformer and depended on them (or the resistance tubes) for comparative temperatures. Due to the uncertainties of obtaining accurate resistance measurements, the top or maximum oil is usually, for comparative purposes, the better criterion. This has been used altogether in comparing observed with calculated values. In order then that this means of heating the tanks affect the accuracy of the readings as compared with an actual transformer, it would be necessary that the temperature gradient of the oil, as affected by barometric pressure, change more under the one condition than under the other condition. There does not seem to be any logical reason why this should be the case.

I agree with Mr. Gray that it is very hard to obtain an accurate law covering the effect of barometric pressure on heating, because in practise this correction is usually small and there are always errors which are liable to creep in. For that reason I do not think we should base any conclusions on, say one test. For my observations, there were three different tests made on each style of tank. An examination of the tabulation of the results will show that although the tests vary slightly, which is to be expected, there are no large variations. This would indicate that the method of making the tests was considerably more accurate than the method usually used in practise.

It is under any condition, a difficult matter to separate radia-

tion from convection, but the law for radiation has been fairly definitely settled and convection follows somewhat the same law, but for smooth surfaces the problem is not as difficult as it would be if we attempted to separate the losses from moving machinery. For the latter condition, the surfaces are more irregular and we do not know the laws, as a whole, under which the heat is thrown out from the machine into the air.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 27, 1916.

THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION

BY F. E. RICKETTS

ABSTRACT OF PAPER

Since electricity has become recognized as the most important means for transmitting energy the value of uniformity in voltage and frequency has become more and more apparent. The phenomenal growth during the last few years in the electrical industry has been due as much to the marked advances in the methods for maintaining a uniform service as to any other cause. During this period of rapid development many papers have been written, setting forth different ideas as to ways of providing against interruptions. At the beginning, these ideas varied greatly, but now there seems to be some hope fôr a more uniform practise as to this type of apparatus.

In writing this paper I have assumed that the field has been pretty well covered so far as the prevention of interruptions goes, but have to call attention to that class of interruptions which so far have been and will likely continue to be unavoidable; and have endeavored to describe certain means whereby the effect of unavoidable interruptions may be reduced to a minimum.

GENERALLY speaking, alternating-current generators cannot be injured by overloading for a few minutes, and since the sudden interrupting of a circuit carrying heavy currents tends to produce abnormal voltages it is very advisable during abnormal conditions on an electrical system to keep all the switches closed except when the opening of a switch or switches is necessary in order to disconnect some section of the system that has become permanently disabled. Especially is this true when we consider the delay usually experienced in restoring service on a portion of a system that has been temporarily cut out, even though there may have been no trouble on that portion.

Since the amount of service affected by the opening of a switch is in proportion to the nearness of the switch to the generator, the importance of keeping the switches closed increases as we approach the generators; consequently the generator switches should be arranged so that they will never open due to any overload, however great the current may be. But for the chance of trouble within the generators themselves, the switches con-

trolling them would be better made non-automatic; however, with such an arrangement, in case a short circuit or a ground should occur within the generator, the service would be seriously disturbed until the operator could open the switch by hand, and there would also be a possibility of the generator being seriously damaged if not destroyed.

Fig. 1 illustrates an ideal scheme for the protection of generators. The generator is three phase, but in describing the scheme we need only consider a single phase as the action of the others will be the same. At each extremity of phase A there is a current transformer, transformer $A1$ being near the oil switch and transformer $A2$ being in this case near the neutral, so that any current passing completely through phase A will produce in the

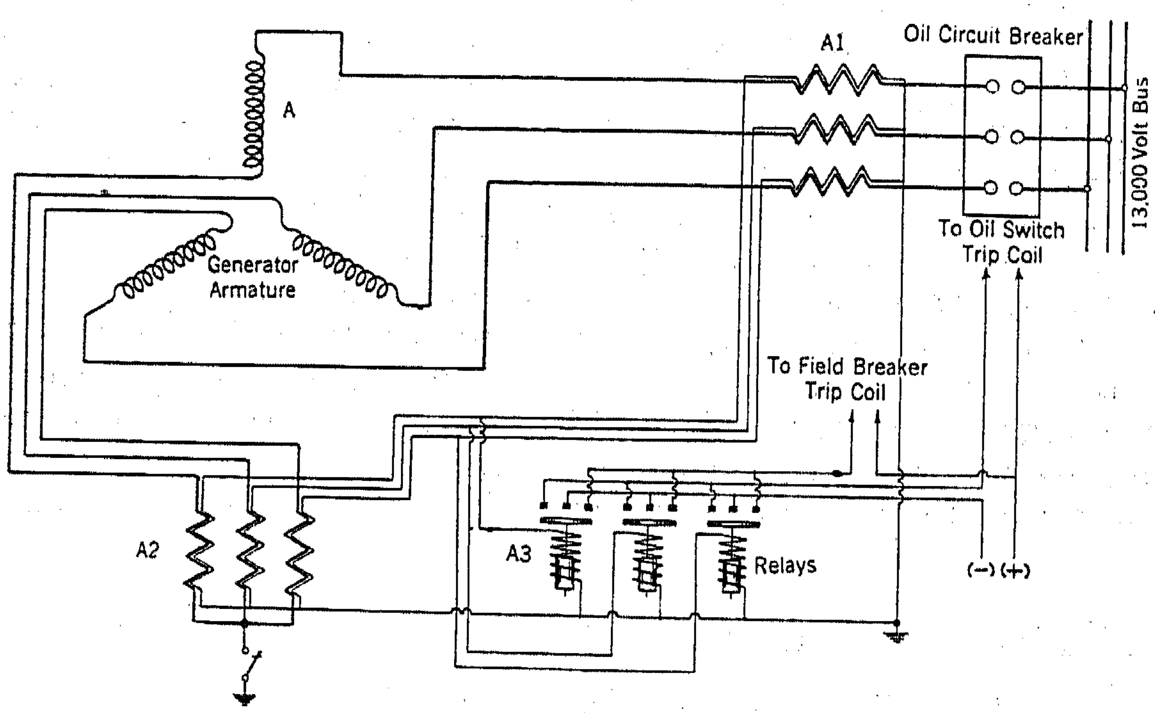


FIG. 1—CONNECTIONS FOR RELAYS ON GENERATORS

secondaries of the two transformers, currents that are exactly equal and in phase, the transformers having equal ratios and connected so that their secondaries will work in series with their instantaneous voltages in the same direction. Then if a relay such as $A3$ is connected with its actuating coil between the two wires connecting the transformers, and its contact circuits connected to both the trip coil of the switch in the armature circuit and the trip coil of the switch in the field circuit, the terminals of the actuating coil of the relay will always be at the same potential as long as there is no leakage of current in the winding of phase A, regardless of the load on the generator or whether it is operating as a generator or motor. Therefore, as long as there is no trouble in the generator, no current will flow through the coil of the relay and there will be no tendency to trip the switch,

but just as soon as current starts to leak from phase *A* to one of the other phases or to ground, there will be a difference in the value of the current flowing through the two transformers, which difference will be represented by a current in the secondary of one transformer, but not in the other; therefore this unbalance in the secondaries will have to flow through the actuating coil of the relay which will cause its contacts to close and instantly open both the armature circuit and the field circuit, thereby not only preventing current from feeding from the bus into the damaged generator, but also preventing the damage that would have been caused by current generated by this generator had the field circuit remained closed.

Now, that we have the generator switches arranged so that they will not open on overload, so long as the generator is in working condition and the other switches on the system assumed to be equipped for selective operation, let us consider what would happen if, when an arc occurs between two conductors of the system at a point where the insulation will not be permanently impaired we simultaneously interrupt the field circuits of all the generators for a short interval of time; say, one or two seconds. When the field circuits of the generators are opened, the voltage of the system will very quickly drop to near zero, especially is this true when the short circuit is severe, in which case the heavy armature current will tend to demagnetize the generators, even before the field circuits are opened. This drop in voltage will be much more rapid than could be accomplished by reducing the voltage applied to the field circuits while the field circuits remain closed since then, as the magnetism of the fields decrease there would be induced in the closed field circuit a voltage that would oppose the decrease in field current. Figs. 2 and 3 give a comparison of the relative time required for the armature voltage to die out when the generator field is opened and when the exciter field is opened. Fig. 2 is for opening of the generator field and Fig. 3 for the opening of the exciter field. If the exciter voltage were lowered by cutting resistance in the exciter field, the time would be still longer. By the time the fields close the arc will have ceased, and as the current builds up in the fields the armature voltage will rise gradually from zero to normal, with total absence of voltage surges and an armature current not exceeding 200 per cent normal. As the armature voltage rises to normal, the service on the entire system will be restored. However, to accomplish the best results, special arrangements of

relays should be provided, and when there are synchronous motors on the system, special features should be incorporated in their design.

To assist in the detail description of this system in practise, Fig. 4 is shown, which for practical purposes illustrates the system as it has been successfully used by the Consolidated Gas Electric Light and Power Company, of Baltimore, for the past three years. A motor M is connected through a train of gears

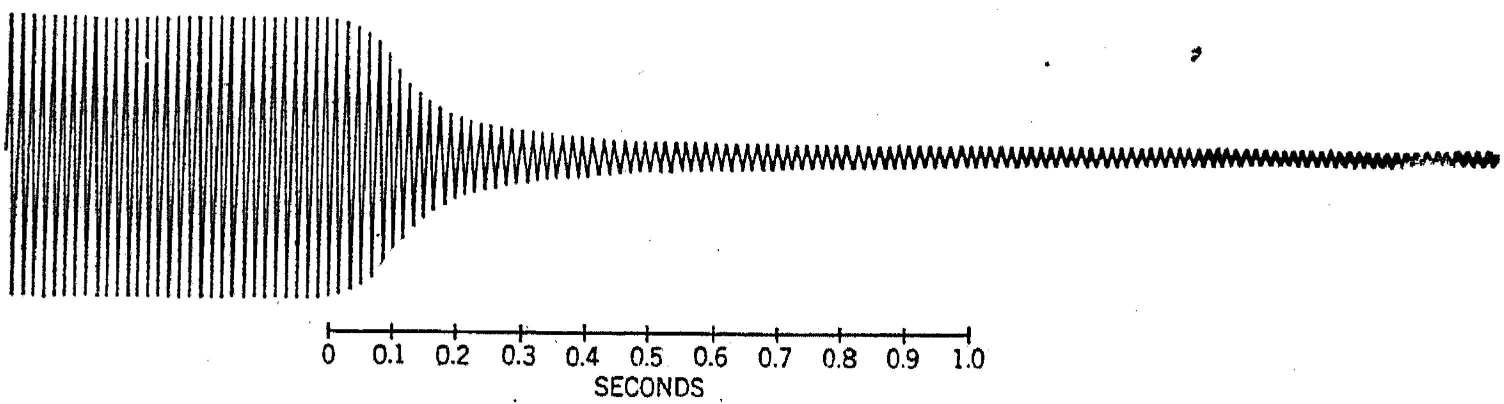


FIG. 2

to a dial switch A in such a way that when the motor is in operation the dial makes one complete revolution in one minute which is the time required for one cycle of operation of the system. The motor is set in operation in response to either of the relays, 1, 2 or 3 which are connected to current transformers in the armature leads of at least one generator that is in operation on the system to be protected. These relays are connected to transformers in the generator leads rather than in any other

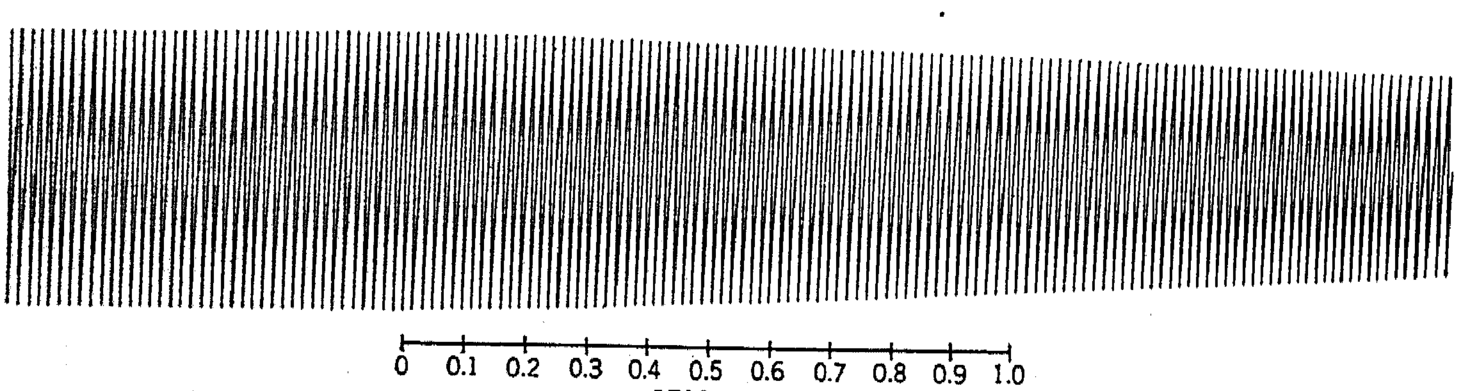


FIG. 3

part of the system for the reason that they will then always be subjected to the same current during a short circuit regardless of the number of generators in service, whereas, if they were placed in the outgoing circuits they would, during a short circuit, be subjected to a current that would be in proportion to the number of generators in service at the time. The action of the relays to start the motor is delayed by a definite-time-limit relay 4 for two seconds in order or give certain of the selective relays

on the system time to operate or cut out a minor circuit that may be short-circuited, but this time must be less than that required to operate the relays controlling the major part of the system. Very soon after the time-limit relay has caused relay *R*1 to pick up and start the motor, segment *B* which is carried by the rotating dial will touch a contact which will apply current to relay *R*1 during one complete revolution of the dial independent of the time-limit relay. This prevents the motor from stopping after it has once started until it has completed one cycle. Immediately after *R*1 is locked a button on the dial touches a contact that closes relay *R*2, which trips out all the field switches, and

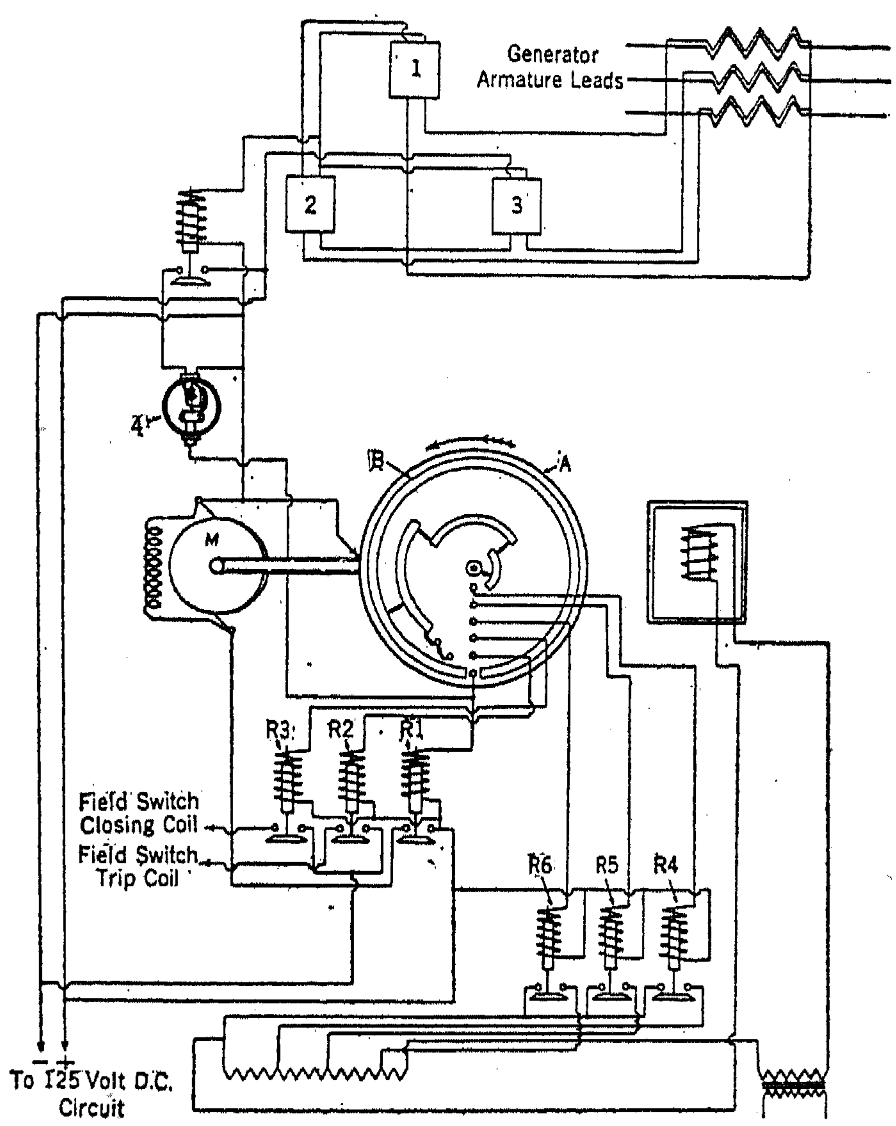


FIG. 4

about two seconds later another button on the dial touches a contact that closes relay *R*3 which closes all the field switches. The voltage regulator will boost the exciter voltage to a maximum, while the fields are opened so that when the fields are closed the field current will build up to a maximum which is very desirable, as the time required for the generators to pull in step varies inversely as the strength of the field currents. However, when the generators pull in step the voltage may rise so rapidly that the regulator will not be able to control it, therefore, to prevent the voltage from rising too rapidly and overshooting, the relays, *R*4, *R*5 and *R*6 are controlled by the segments near the center of the dial so that during the first one-third cycle of opera-

tion, one-half the resistance in series with the voltage-regulating coil of the regulator will be short-circuited and the resistance will be cut in circuit in steps as the dial rotates, all of the resistance being in circuit at the end of the cycle.

Therefore, since the regulator operates to maintain a constant current in the voltage coil, the voltage will be maintained in proportion to the resistance in the circuit of the voltage coil; that is, the voltage will be restored to normal gradually, which is of great importance in pulling the motors on the system into synchronism.

During the operation of the device, the induction motors will slow down and come back to normal speed, but the relays controlling them should be set for a rather high current, say 400 per cent load to prevent them from tripping before the motors are up to speed. This high setting will not be dangerous as the motors will stand a heavy overload for a few seconds without heating to a dangerous temperature, and in case a motor burns out sufficient current will flow to trip the relay.

Synchronous converters present a more difficult problem since they lose a great part of their torque when they get out of phase, and their polarity on the direct-current side depends upon the polarity of the brushes when they come into synchronism, there being an equal chance that they will have one polarity or the other, since the polarity of the brushes changes every time the armature gains or loses one pole.

This reversing may be overcome by exciting the fields from an external direct-current source which is not disturbed by the short circuit so that the converter armature will not lock in step when the brush holders are of the wrong polarity. This separate excitation need not be equal to that at which the rotary normally operates; in fact, it should not be of full value as it may cause the converters to flash at the brushes as they are pulling into synchronism. In most cases 25 per cent full value of field current will insure the polarity being correct. Fig. 5 illustrates one method that has been successfully used to accomplish the above result. A converter 1 is connected to the positive and negative buses through automatic circuit breakers and has its neutral grounded. There is also a storage battery 2 connected to the buses to take the load during short interruptions on the alternating-current system. When the fields of the generators open and the voltage decreases, current will flow from the battery into the converter until the breakers open. Then, since the voltage of the rotary is not sufficient to hold up the relay $R1$, the plunger

of this relay will drop, opening its own circuit and closing that of relay $R2$ which connects the negative bus to a point between the field coils and the rheostat, so that current will flow from the ground through the transformers to the armature and thence through the field coils and rheostat in multiple to the negative bus, the voltage impressed on the field coils being half normal and in the direction to give the proper polarity at the brushes. Therefore, when the converter comes up to speed it will be ready for service.

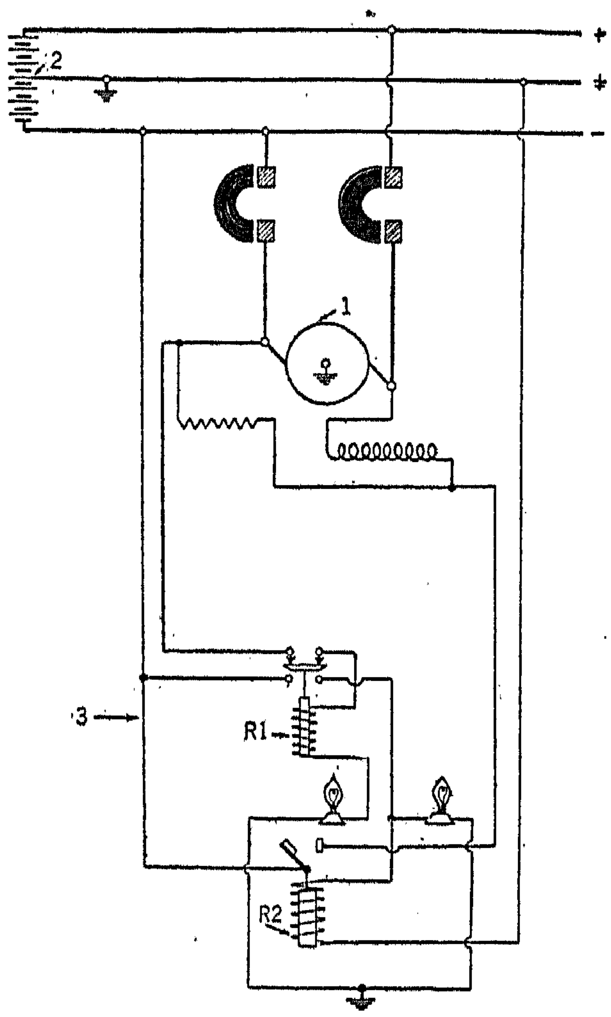


FIG. 5

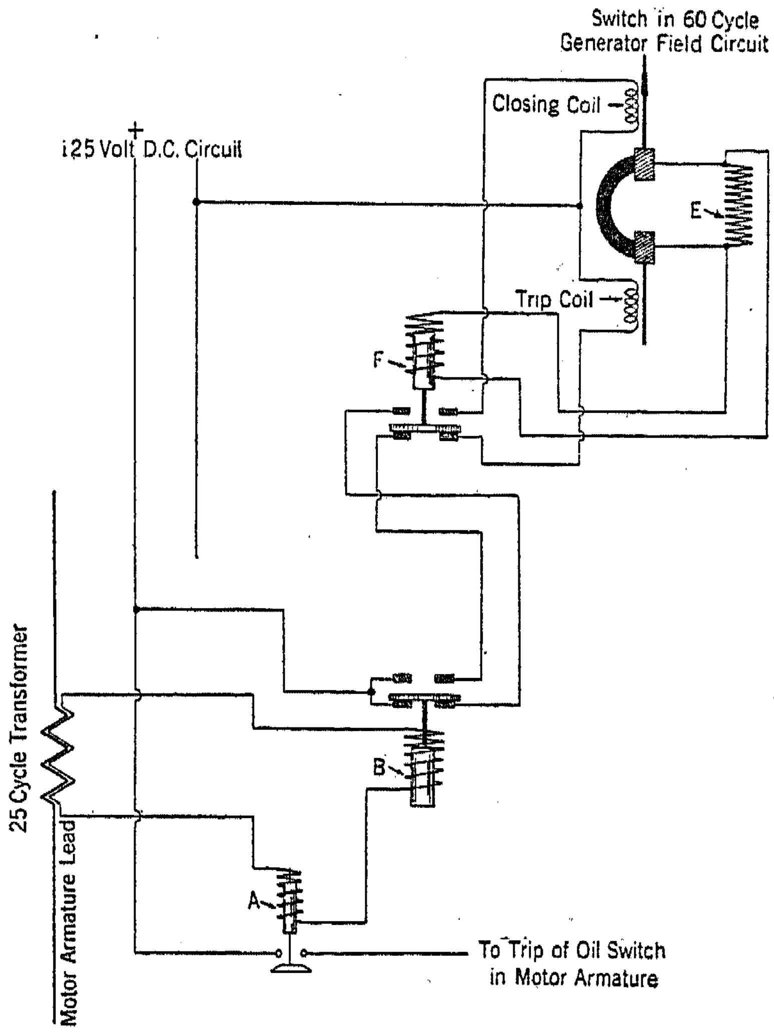


FIG. 6

Generators	Resistance	Capacity
5000 kv.a.	0.5 ohm	150 amp.
3000 "	1 "	75 "
1000 kw.	2 "	50 "

When no battery is used on the bus, a small battery capable of furnishing the field current should be connected between the neutral and wire marked 3 which would then not be connected to the negative bus. In order to prevent the relays controlling the a-c. side of the converter from tripping while the converter is out of synchronism, they should be set for about 400 per cent normal load.

With synchronous motors the problem is more difficult, since they lose a part of their torque as soon as they get out of synchronism. In this case it becomes necessary to reduce the load to a point where the motor will pull in step. One method of accomplishing this is shown in Fig. 6 which illustrates the connections for reducing the load on a motor-generator until the

motor can pull in. A single armature lead is shown, as the connections to the others are similar. In this armature lead is a current transformer which furnishes current to two relays one of which *A* is connected to trip the main switch controlling the motor, is set for 400 per cent load and should have an inverse-time characteristic such that it will trip in about one-third of a second at the maximum current the motor will feed into a short circuit; then it will not trip under heavy load or when a short circuit occurs on the system, but will act very quickly when trouble occurs in the motor. This protection could also be accomplished by the scheme recommended for generator protection earlier in the paper; however, the arrangement shown in Fig. 6 has the advantage of protecting the motor should it get out of step and for any reason be unable to regain synchronism. There is also in the circuit of the current tranformer a relay *B* which is so designed that it will pick up at a current corresponding to 200 per cent load of the motor, and after it has once picked up, it will not drop till the load on the motor is normal. Responsive to the relay *B* is a switch in the field circuit of the generator, which has connected in parallel with it a resistance *E* that, when in circuit, will limit the load on the generator to a point where the motor will pull into synchronism. Therefore, as the voltage on the system builds up after an interruption, before the current in the motor is great enough to operate relay *A*, relay *B* will pick up and trip the field switch, which will cut in the resistance *E* and thereby limit the load on the motor to a point where the motor can pull in without operating relay *A*. It will also be noted that there is a relay *F* which picks up in response to the voltage across resistance *E*, and opens the circuit of the trip coil of the field switch and closes the circuit of the closing coil, so that when the motor pulls into synchronism and the current decreases to normal the field circuit breaker will be closed and the voltage on the generator will be restored to normal; also the voltage across relay *F* will drop to zero and it will reset itself.

The design of synchronous motors affects to a great extent their ability to pull back into synchronism, the greatest item being the resistance of the damper winding. Some motors will not pull back without any load with full voltage applied to the armature, while others with properly designed damper windings will pull back as much as 65 per cent of full load with only 80 per cent of full voltage on the armature. I know of one machine that would not pull in without load that pulled back with full

load after its poles had been replaced with ones with very low resistance dampers. However, these low resistance dampers give very low torque at low speed and make it practically impossible to start the motor by applying low voltage at normal frequency to the armature, making it necessary to start with an induction motor. When a heavy current flows in the armature of a synchronous motor while it is out of phase, the fields are subjected to a considerable stress by induction and it is therefore advisable, though not necessary, to insert reactors in the armature leads. This reactance should bring the total of the circuit to about 20 or 25 per cent, and can be provided in the winding of the motor in new machines. This reactance may seem rather high but the motors can be operated at unity power factor under which condition it will have no bad effect, and when the motor gets out of synchronism, the inductance of the armature will be high and its voltage will be in phase with that of the reactance, therefore the voltage across the armature windings will be materially reduced. This is shown graphically in Fig. 7. *A* shows the distribution of voltage between the armature and reactance when the motor is operating at 100 per cent power factor while *B* shows the same when the motor is running out of synchronism.

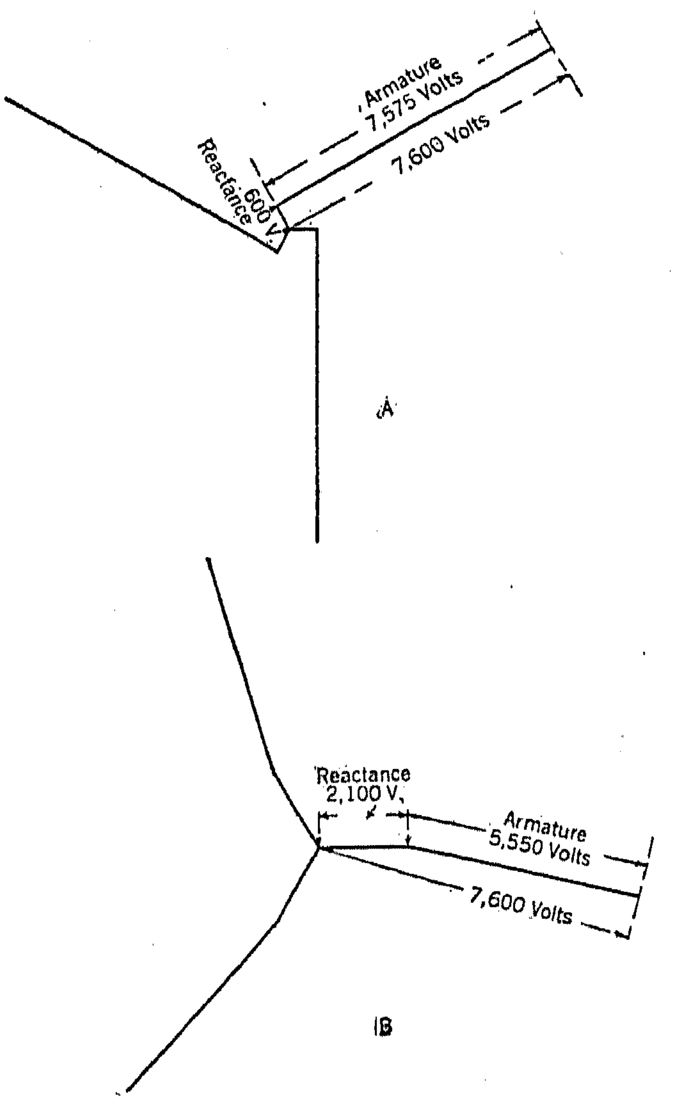


FIG. 7

Fig. 8, which shows a portion of a voltmeter chart taken at a generating station protected by this system during an electrical storm, illustrates the effect of lightning strokes on the service. The voltage was compensated for constant voltage at the supply point, therefore the shape of the curve shows the amount of load dropped and the rate at which it was restored.

The troubles at 4.14 and 4.18 were cleared by the fields being opened after the trouble had been on for four seconds. The trouble at 4.22 was cleared by other devices before the short circuit had been on long enough to cause the fields to open. It will be realized that the instant a severe short circuit occurs the substation machines begin to slow down and, when the fields

are set to open after four seconds, will be considerably below speed even before the short circuit is cleared, which adds to the delay in restoring normal conditions.

Fig. 9 shows a section of a voltmeter chart recorded at the same generating station as that shown in Fig. 8. Here the fields of all the generators were opened for one second while there was no trouble on the system, and it will be seen that there was no loss of load. It will be evident that if the fields were set

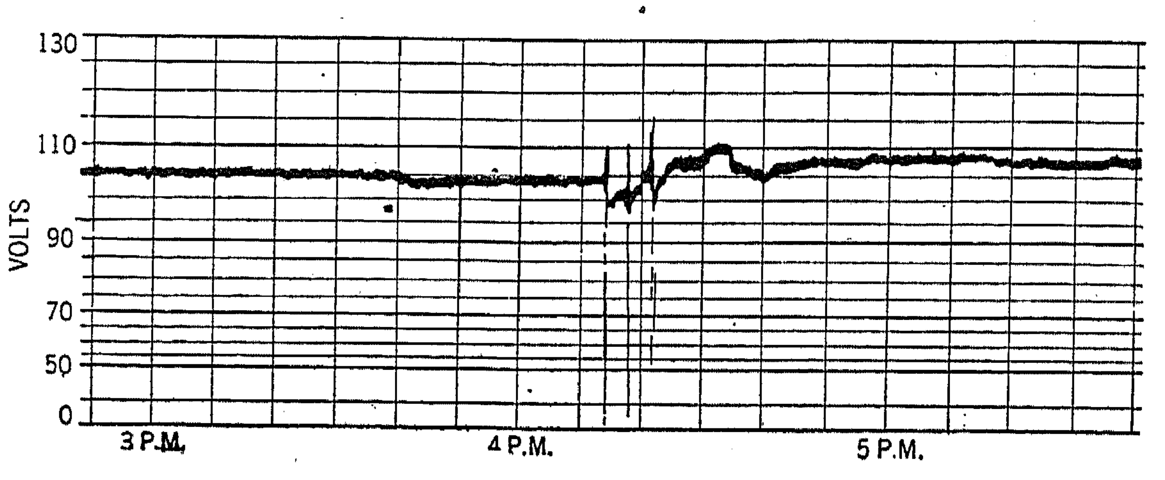


FIG. 8—VOLTMETER CHART, JUNE 21, 1913, HOLTWOOD POWER STATION

to open instantly when a short circuit occurs, the system could be restored to normal with no more disturbance than would be caused by a short circuit that was cleared by the opening of an oil switch set for one or two seconds. However, in this case the overload relays would have to operate after the fields closed, when the trouble was of a permanent nature.

In practise, this system has proved of great value in clearing

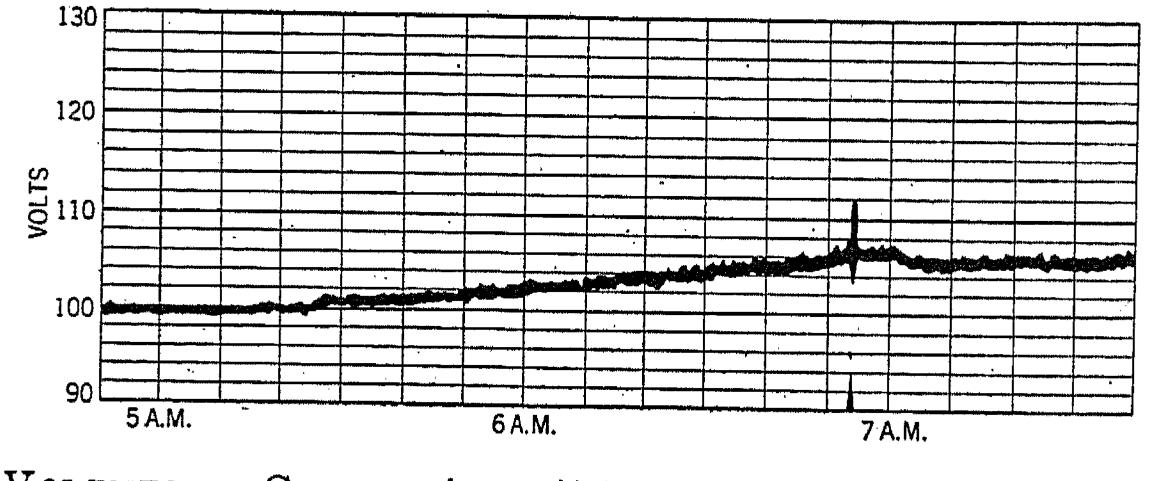


FIG. 9—VOLTMETER CHART, AUG. 7,1913, HOLTWOOD POWER STATION

short circuits in the main bus structure, such as are sometimes caused by the failure of an oil switch or the accidental starting of an arc between buses. A further advantage is gained in starting a system after a general shut down, which can be done by closing all the alternating-current switches while the fields are open, and then, when the fields close, all the generators will synchronize and bring the entire system up to normal, no telephoning being necessary, as the voltage will build up gradually and therefore

not damage any machines that may be left in service. This may be done even in cases where the service has been off for 10 or 15 minutes. When there are several generating stations operating in parallel there is no difficulty in getting the field breakers of all generators open at the same time, since the short circuit strikes all the stations simultaneously. If some of the breakers open a little before the others or if some of them do not open at all there is no bad effect.

Up to this point I have discussed only that class of interruptions that affect the entire system. There is, however,

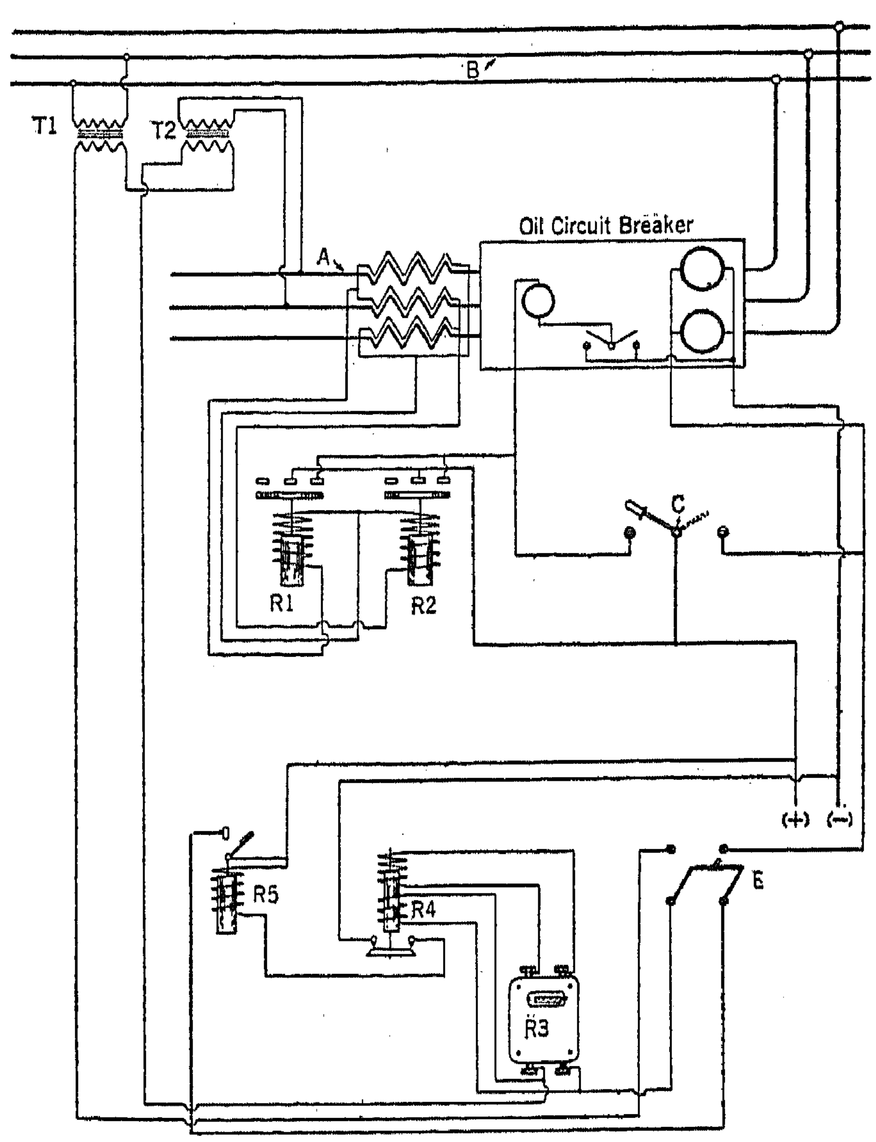


FIG. 10

another class which affects only a minor part of the system, for example alternating-current distribution feeders that are not tied in with other feeders after they leave the station. More than 50 per cent of the short circuits on these feeders are of a temporary nature, and therefore clear themselves as soon as the feeder trips out; but by the time the operator can close the switch again the motors have shut down. This in effect gives an interruption of several nimutes as the customer will be slow in starting up. Since an arc breaks within a fraction of a second after the voltage is cut off we may, by closing the switch quickly, prevent the motors from shutting down.

Fig. 10 illustrates a system that has operated very satisfactorily

to clear temporary short circuits on distribution feeders, when the short circuits are of such a nature that they will not re-establish themselves after the arc is once broken.

A feeder *A* is connected through an electrically-controlled oil switch to a station bus *B*. The switch *C* is for operating the switch manually, and relays *R*1 and *R*2 are for tripping the switch in response to current in the feeder, and serve the purpose of the usual overload relays. Transformers *T*1 and *T*2 are

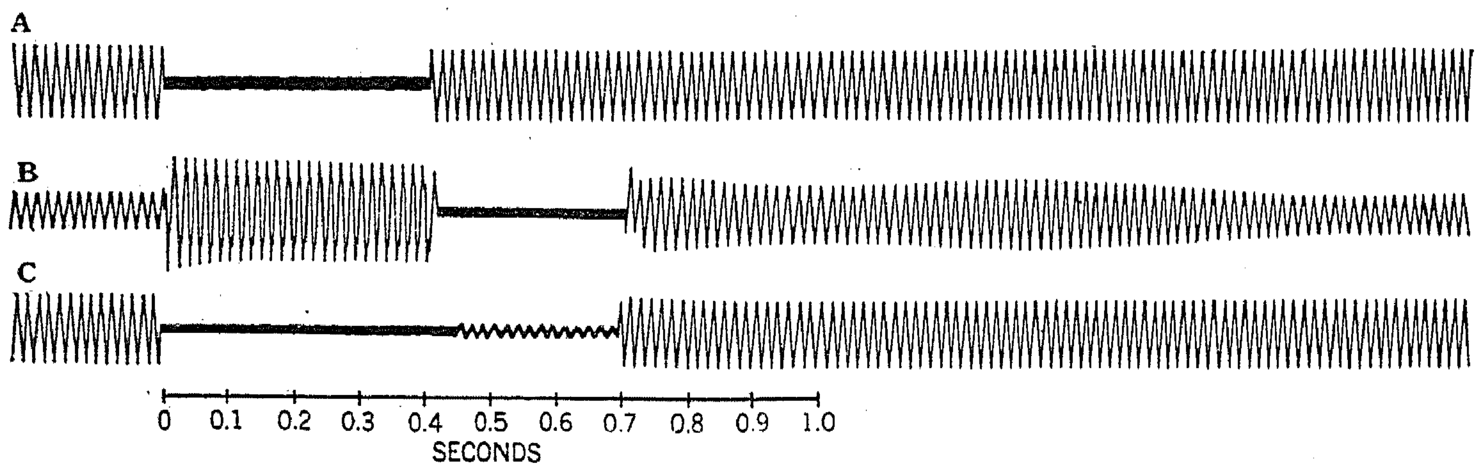


FIG. 11

connected one on either side of the oil switch, and in such a way that when the oil switch is closed their voltages will oppose each other, and therefore there will be no voltage impressed on relays *R*3 and *R*4. Then, when an arc occurs on the feeder, either of the relays *R*1 or *R*2 may trip the switch but as soon as the current is interrupted by the oil switch the voltage on the two transformers *T*1 and *T*2 will become unbalanced, which

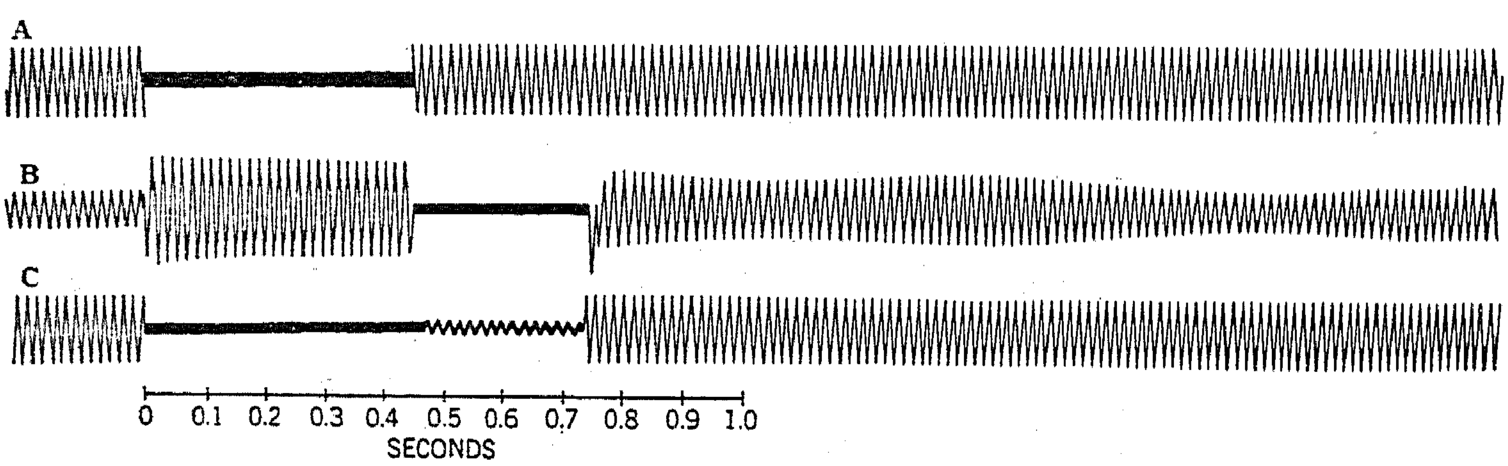


FIG. 12

will cause current to flow through relays *R*3 and *R*4; *R*4 will pick up instantly, but *R*3 being a time-limit relay will start to move but will not close its contacts for a predetermined time. When relay *R*4 closes its contacts, current will flow through relay *R*5, which will close its contact, and thereby close the oil switch. If the short circuit is still on the feeder when it is made alive, relays *R*1 and *R*2 will trip the switch again and *R*4 and *R*5 will close the switch as soon as the potential across the switch is

unbalanced. This opening and closing of the feeder switch will continue until the relay $R3$ closes its contacts, thereby short-circuiting the upper coil of relay $R4$, which will prevent this relay from further operation until the voltage across $R3$ has been reduced to zero for sufficient time for it to return to its starting position. This is done after the trouble on the feeder has been cleared by opening switch E and closing the oil switch by means

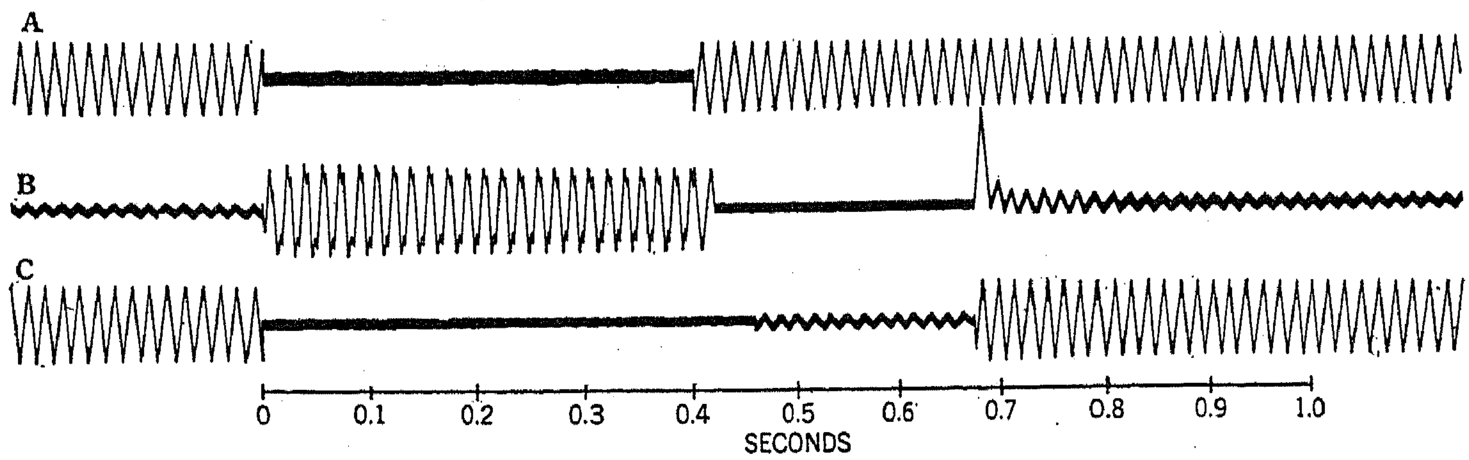


FIG. 13

of switch C; then the system can be put in operation again by closing switch E. If the arc breaks the first time the oil switch opens, $R3$ will return to its starting position making the apparatus self-setting.

In order to illustrate the accuracy with which this system operates, and its effect on the service, I have shown oscillograph records, Figs. 11, 12, 13, 14 and 15, which were taken on a 6600-volt system protected by this method. The arc was

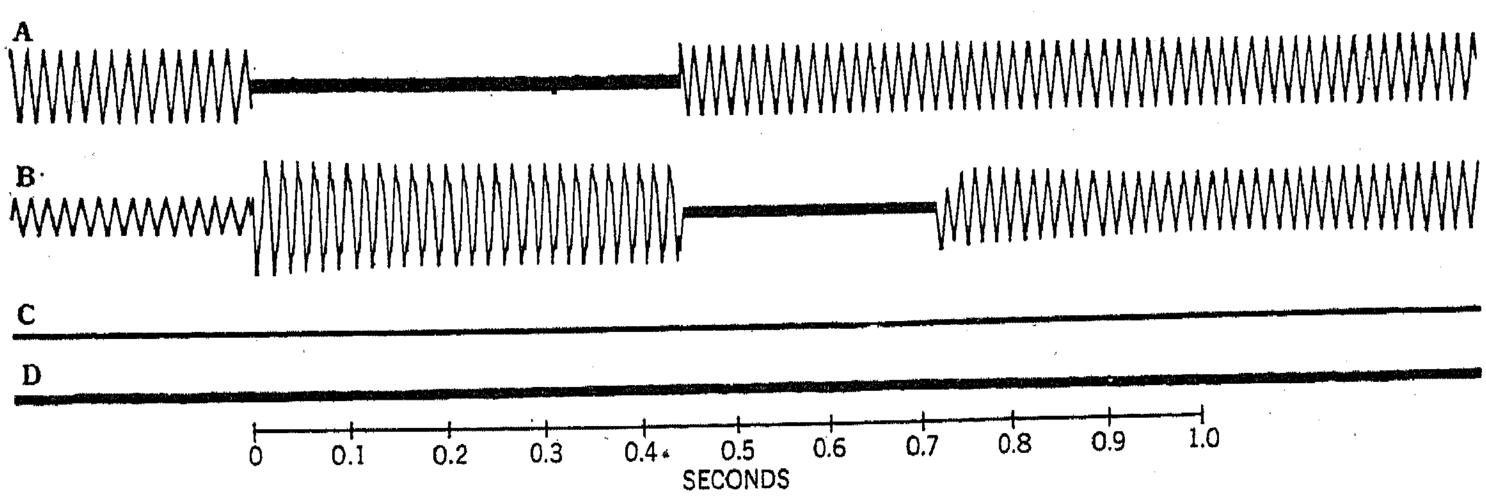


FIG. 14

started by throwing a one-inch (2.54 cm.) spark gap, short-circuited by a fuse wire, across the circuits.

In Figs. 11 and 12, A shows the bus voltage B the current in one leg of a 200-h.p. induction motor carrying full load, and C the voltage on the feeder. To make the test most severe, the short was made near the switch and the load on the motor was provided by a direct-connected generator supplying current to a resistance, so that the fly-wheel effect would be very small. It

will be noted that the time of operation was the same in each case and that the load was not very great after the operation. The conditions under which Fig. 13 was taken were the same as for Figs. 11 and 12, except the motor was running idle. In Fig. 14, *A* gives the voltage on the bus, *B* full-load current in the motor, *C* the voltage of the direct-current generator and *D* the zero line for *C*. It will be noted here that the direct-current

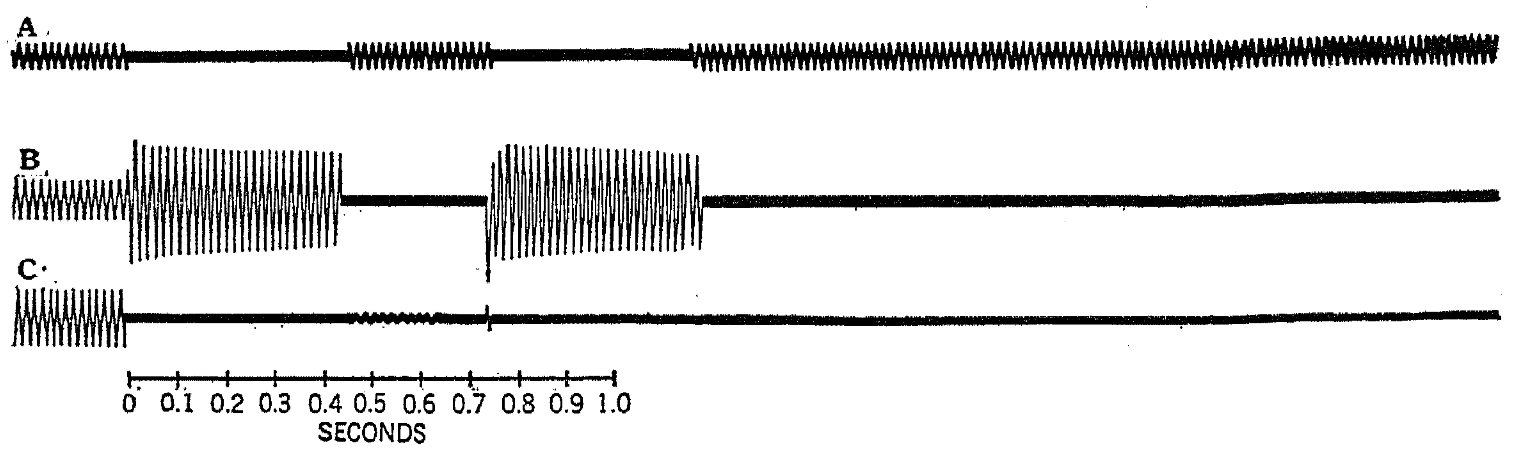


FIG. 15

voltage remained practically constant showing that the speed of the motor did not drop off materially. Fig. 15 was taken under the same conditions as Figs. 11 and 12 except the spark gap was made so the arc would not break. This shows how the number of operations was limited.

Fig. 16 shows the operation of the system with a later type oil switch; *A* is the voltage across the switch and therefore shows

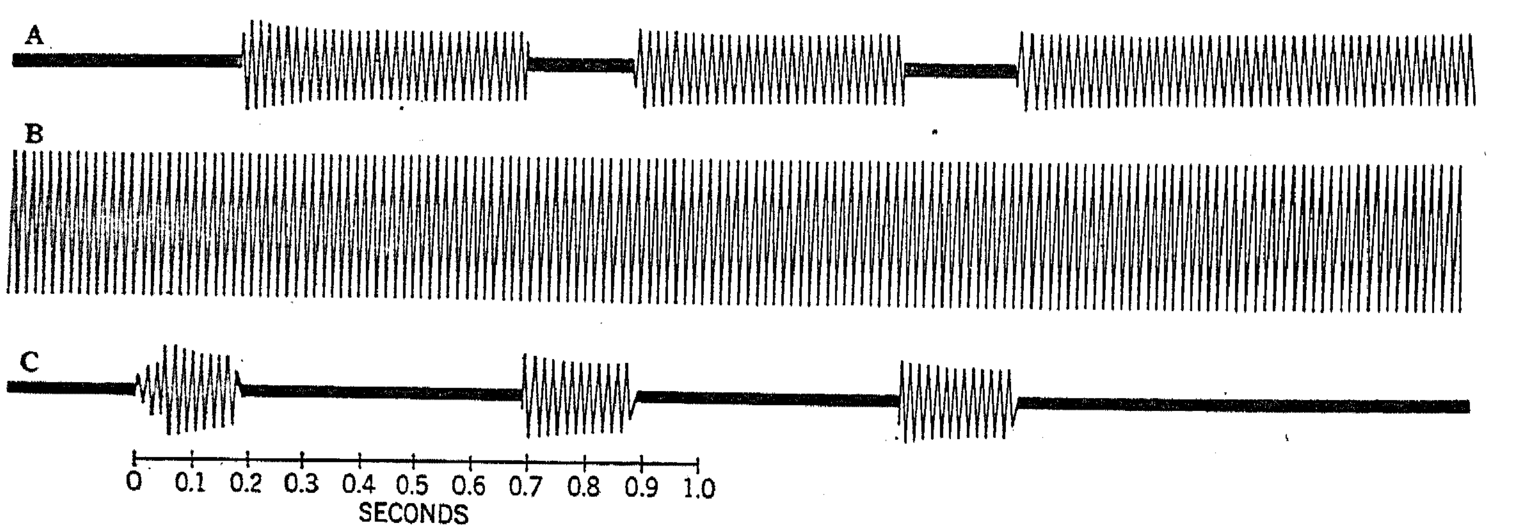


FIG. 16

the time the switch was open, *B* is a timing curve taken from a circuit of $62\frac{1}{2}$ cycles and *C* shows the current in the short circuit. It will be noticed that the switch opened much quicker and closed slower than the old type switch used in the other tests; the total time of operation, however, was about the same.

The tests shown above have been repeated many times and in no case has the time required for similar operations varied more than one fiftieth of a second.

DISCUSSION ON "THE RESTORATION OF SERVICE AFTER A NECESSARY INTERRUPTION" (RICKETTS), CLEVELAND, OHIO, JUNE 27, 1916.

Harold Goodwin, Jr.: These relays presented by Mr. Ricketts in this paper are most interesting, and the results of the operation of the system of the Baltimore Consolidated Gas, Electric Light & Power Company, particularly in connection with the current received from Holtwood show their very great efficiency.

There is one particular point to which I wish to call attention and that is where the text reads: "During the operation of the device, the induction motors will slow down and come back to normal speed, but the relays controlling them should be set for a rather high current, say 400 per cent load, to prevent them from tripping before the motors are up to speed." That is all right, I think, if the motors are all equipped with relays, and if all of the motors were in power plants handled by operatives, but as the system reaches out and reaches down to the smaller users of current, motors are connected without relay equipment but simply fuses. Were all the fuses capable of carrying 400 per cent normal current they would fail in their original purpose of protecting the motor under abnormal conditions and the distribution system under starting conditions. Without going into details let us note that the original purposes of a protective device need serious consideration before an extreme setting is adopted.

R. F. Schuchardt: Fig. 1 shows a balanced relay protection, regarding the efficacy of which I can give testimony. On the system in Chicago we recently had a breakdown in the armature coil of a generator protected with a scheme very similar to that shown by Mr. Ricketts. The generator switch and the field switch were very promptly opened by the relay and the damage in the generator was limited practically to a single coil. The value of the relay in this operation can be better understood by comparing with similar breakdowns which occurred years ago before reactors were installed, the generators having no relays of any kind. In all of these cases the operator, who has a clear view of the generators, saw the flash and very promptly opened the switch but almost invariably all coils were damaged.

The very interesting scheme described, in which the field circuit is opened during certain cases of trouble, is apparently applicable primarily to overhead transmission lines and considerable modification would be necessary to apply it to underground systems. The arrangement shown in Fig. 10 can be applied to distribution circuits almost universally and is of particular value where these circuits are overhead and where disturbances which cause the switch to open are often only momentary. It would be worth while to work out a modification

of this scheme applied to an automatic pole-type switch connecting branch circuits, thus reducing the extent of interruptions and thereby still further improving the high record of continuity of service which is now enjoyed by modern systems.

H. R. Woodrow: I agree with Mr. Ricketts regarding the installation of relays on generating circuits. As we have found, the burnouts in generators rare, and the reliability of present automatic devices somewhat questionable, we have considered it wise to keep the generator switches non-automatic.

In the generator balanced protective arrangement described in the paper, a loose cable contact, or a slight difference in current transformer characteristics, might cause the relays to operate on straight overload. I would like to inquire if this has ever occurred on any of the systems using this form of protection.

The wonderful improvement in sensibility and reliability of reverse-power relays looks promising for an application in making generator switches automatic.

I would like to ask Mr. Ricketts a question regarding the opening of the generator field circuit. In our experience the opening of a generator field switch has always caused a heavy voltage disturbance on the exciter system. Quite recently a single-phase short circuit occurred in a generator which produced high alternating currents and voltages in the field circuits, causing a severe disturbance on the whole excitation system and control system, which happened to be connected at that time to the exciter bus.

In cases where a considerable generator field resistance or long cable runs are in series with the field circuit, an opening of the field circuit will undoubtedly cause a heavy voltage disturbance in these circuits.

I would also like to inquire if there is any provision made for the speed control when the field circuit is opened? That is, any provision to keep the speed down, as the speed will rise very rapidly if the field circuit is opened and the load is taken off.

Also, when the generators are thrown back in service, what provision is made to prevent arcing at the commutators of the exciters? In one case that I know of, it was attempted to restore service in the manner described, which resulted in serious damage to the exciters by arcing across the commutator. In this case, however, there was no battery floating on the excitation bus.

In general, I do not believe the principle of restoring service as described would be very advantageous to a large concern where there are a large number of underground cable lines, as we very rarely find, in such cases, a disturbance on the system which will clear itself if the voltage is taken off.

We have used to good advantage, on overhead lines, the principle which the author refers to in Fig. 10, but with hand-operated switches. The switches are automatic and they are immediately thrown in once or twice by hand, after they have automatically opened; and in cases of the principal circuits,

the operators are instructed to throw the switches in at least twice after they have automatically opened during a lightning storm. In over 50 per cent of the cases the service is restored without further disturbance.

I wish to bring out one point as a warning in accepting this method of restoring service; that is, this method cannot be used unless the switches are completely automatic. That is, unless they will immediately open if thrown in on a short-circuited feeder.

E. T. Street: I notice that the scheme devised for protecting the generators will multiply very largely the number of current transformers on the system. The current transformers on our system have given us a good deal of trouble, and I am of the opinion from what I have read, and I ask if it is correct, that the burning out of one current transformer would shut down the entire station until the transformer was found and isolated. If that is true, I am afraid that the scheme will increase the liability of serious trouble from a small cause.

George A. Burnham: There is one point which might be worthy of consideration, in reference to the elimination of potential on the system to reduce the trouble as a whole, caused by a fault in one of the generators.

It would appear to be a disadvantage to reduce the potential to zero for the length of time which Mr. Ricketts states, in view of the fact that in nearly all of the industrial plants either the individual switches which control the motors or the service switches are equipped with no voltage release of the instantaneous type and the loss of potential at these attachments would undoubtedly disconnect a very large portion of the load on the system.

The arrangements which Mr. Ricketts has described, could, it seems to me, be utilized more effectively and with less liability to interruption of service, if, instead of opening all of the field switches of the generators on the occurrence of the fault in one generator, the balanced relay tripped only the switch of the faulty generator and then allow the movement of the generator switch to disconnect the generator field switch subsequently or simultaneously. This would reduce the potential to zero on the faulty generator instantly after it had been disconnected from the bus and prevent further destruction. It could easily be arranged so that the aforementioned generator field switch would be non-automatic, except when rendered automatic by the operation of the balanced relay, by the addition of an extra contact on the relay which would be connected in series with a circuit-closing switch on the main generator breaker. With this arrangement it would appear to me that the faulty generator could be very satisfactorily disconnected and the potential removed from said generator in order to eliminate further destruction, without it being necessary to remove the potential from the entire system.

John B. Taylor: From the discussion it appears that some members approve certain features of the automatic system, but doubt how far operating and other conditions may be comparable to the systems with which they are more familiar. Devices such as these cannot be applied indiscriminately to any existing system, since much depends on the character of the load; the ratio of cable mileage to overhead lines, the transmission and distribution voltages and the principal causes of interruption.

L. N. Crichton: The part of Mr. Ricketts' scheme that appeals to me most is the service restorer device. Mr. Ricketts has taken quite an active part in the advance of the automatic sectionalizing and it is fitting that he should turn his attention toward methods for restoring service after, for any reason, a circuit has been disconnected.

I recently had the pleasure of seeing that automatic service restorer device in operation, and it was quite remarkable as to the rapidity with which the various pieces of apparatus were put in motion, although there was no induction motor or any load of that kind at the point where I saw the test being made, and I doubt very much whether a man at some little distance away from the motor would have known there had been any momentary interruption of service at all.

It seems to be a scheme particularly useful for high-voltage lines distributing small amounts of power, where the lines extend out in the country for a good many miles, and where lightning conditions are such that if a scheme of that kind is not adopted reliable service could not be given to a good many classes of service. I believe there will be quite an advance in the art of giving continuous service by the use of this device.

Joseph T. Kelly, Jr.: With regard to the point which Mr. Goodwin made, relative to the 400 per cent set of motor relays, I can only say, that the system has been in operation now for something over two years, and we have never heard of a case of trouble of that sort. In fact, as was stated here a moment ago, in most cases—I suppose very close to one hundred per cent of the cases—customers never know that there has been an interruption on the feeder service. Looking at the lights, there is a barely preceptible blink, and looking at a motor it is almost impossible even though watching for it, to notice that there has been any slowing down in the motor at all.

Regarding the application of the scheme to hand-operated switches, so far Mr. Ricketts has not been able to do much work along that line. As a matter of fact, there is one remaining substation of the Consolidated Company equipped with hand-operated switches, and at the present time work is under way to replace all that switchboard equipment with electrically-operated switches equipped with this system, and when that is done all of the substations of the Consolidated Company will be equipped in this manner.

As to the opening of the field circuit causing a disturbance on

the exciter system, the point mentioned by Mr. Woodrow, all of our exciters have storage batteries connected with them, and that, doubtless, makes a difference. We do not have any trouble whatever due to the opening of the field switches.

As to the matter of the application of the device to underground cables, of course, when an underground cable breaks down usually the trouble is not of a nature, which clears itself when the potential is cut off. It is usually a permanent breakdown, and consequently though removing the potential and then re-applying it, the trouble would still be present. However, there are cases in which the cable heals itself or will not reestablish an arc when the arc has once been broken. In any event, the momentary application of voltage to the cable cannot do any harm, because the whole cycle takes place in about 7/10 of a second, and there cannot be a sufficient flow of current into the fault in that length of time to cause disastrous results, so that even on an underground system there can be no harm in using this system, and to that extent, I would say, it is not limited to the overhead system. In fact, on the Consolidated system, every feeder going out of a substation, goes out under ground for a greater or less distance, and the automatic opening and closing device is applied to these feeders impartially.

If the trouble is on the overhead, and transient, or if the trouble is on the underground, and clears itself, the system works. Of course, if it is a permanent short circuit the system will not work, and in that case, after the predetermined number of automatic closings the switches will remain open. In our system they are set to close three times, and if they open the fourth time the switch remains open until manually closed.

Mr. Sweet raised the question about the burning out of current transformers. As I understood it, that was in connection with the first scheme for protection of generators. In that case, there are two current transformers, one on each side of the winding of the generator—if either of these burned out, there would, without doubt, be an unbalanced current in the secondaries; in other words, the current in the two current transformers, the one faulty and the other not faulty, would not be maintained, equal, and consequently the relays would operate to cut that generator out of service, including the transformers connected to it, and the system would not be interrupted.

Mr. Burnham raised the point about trouble in a generator causing an interruption on the whole system. That would not be the case because as shown in Fig. 1, in Mr. Ricketts' paper, covering the case of trouble in a generator, if trouble occurs, that generator will be disconnected from the circuit without opening the fields on the rest of the apparatus.

Replying to Mr. Taylor regarding the system; that of the Baltimore Consolidated Gas, Electric Light & Power Company is a 2300/4000-volt four-wire distribution system, the transmission voltage between substations being 13,200 volts with a

grounded neutral, and the field-opening device is also used on the 60,000-volt transmission line from the generating station of the Pennsylvania Water & Power Company at Holtwood, Pennsylvania, to Baltimore, although, as Mr, Ricketts mentions incidentally in his paper, in that case the timing device is set for four seconds instead of two seconds, as used in the Consolidated system. The reason for that is that the Pennsylvania Water & Power Company also uses the Nicholson device and Mr. Ricketts' field opening device is so set as to give the Nicholson device a chance to operate first, and then if that fails to clear the trouble, or does not succeed in entirely clearing the trouble, then the field opening device will operate. As Mr. Ricketts points out, that delay of four seconds imposes very much more severe conditions in restoring service.

I have not in mind figures as to the relative amounts of underground and overhead feeders in our system—every feeder, as I said a moment ago, goes out from the substation underground, and the overhead portion is limited to the acutal distribution portion of the feeder; many of the feeders distribute entirely underground, and the system is applied impartially to all feeders. The capacity of our generating station at the present time is approximately 35,000 kv-a. nominally, and will be increased within the next couple of months to about 70,000 kv-a.

I might say, in closing, that the proof of the pudding is in the eating. This system was first applied to a suburban substation at which no operator is kept, something over two years ago, and it has operated with the greatest satisfaction. When a feeder trips out, a relay closes a contact and rings an alarm bell in the office of the district foreman, about three-quarters of a mile distant. That bell may either make two or three, or even one short indication, or it may make three short indications and then continue to ring. In other words, if a feeder drops out and restores at once, and stays in, the alarm bell will so indicate. If it drops out twice and restores itself, the same. If the feeder stays out, the alarm bell continues to operate. So with no operator within three-quarters of a mile this substation is taken care of by this device, and it has been in satisfactory use there for about two years and a half. About one year ago five other substations were equipped with this system, and at the present time the apparatus is ordered with which to equip the last of the substations of the company.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 28, 1916.

STUDIES IN LIGHTNING PROTECTION ON 4000-VOLT CIRCUITS

BY D. W. ROPER

ABSTRACT OF PAPER

Investigations forming the basis of the paper have been carried on for a period of five years. They were made on a system which at present supplies service to 250,000 customers over some 3000 miles of circuit, through about 16,000 transformers. During the experiments a number of theories have been tried out in practise and the results of the experiments are given in some detail. At the beginning of 1915, three distinct types of arresters and three schemes of protection were in use. The conditions during the year 1915 and the records obtained from lightning storms during the year are set forth by means of a number of maps, drawings and tables. An analysis of the results is followed by a list of conclusions.

The several methods of improving the lightning protection have together resulted in eliminating over 90 per cent of the troubles from lightning.

I—DESCRIPTION OF THE SYSTEM

THE DISTRIBUTING system on which the investigations herein contained were made, covers about 180 square miles in the city of Chicago, and supplies about 250,000 customers through about 16,000 transformers. During the five years covered by these studies, the load has increased from 28,600 kw. to 73,900 kw. The system of distribution is four-wire, three-phase, with 2400 volts (nominally) between each phase wire and the neutral wire, the latter being grounded only at the sub-stations. The system is supplied by 125 feeders from 15 sub-stations, as shown in Fig. 1. All of the feeders leave the sub-stations in four-conductor underground cable, of which there are over 200 miles (321.8 km.) On the average the feeders extend, therefore, nearly two miles (3.2 km.) underground before connecting to the overhead lines, and the length of the overhead feeders is about 25 per cent of the total length. There are, roughly, 3000 miles (4828 km.) of primary distributing mains of which less than 10 per cent is underground. About 100 of the distributing transformers are located in manholes or in transformer vaults on the customers' premises. All of the

transformers are connected between the neutral wire and one phase wire, and in the three transformer three-phase installations there is no connection to the neutral wire of the circuit.

There were 15,605 transformers connected to the line on August 1st, 1915, and all of the percentages for that year were based on the records of transformers installed as of that date. A map of the city showing the distribution of transformers is shown in Fig. 2.

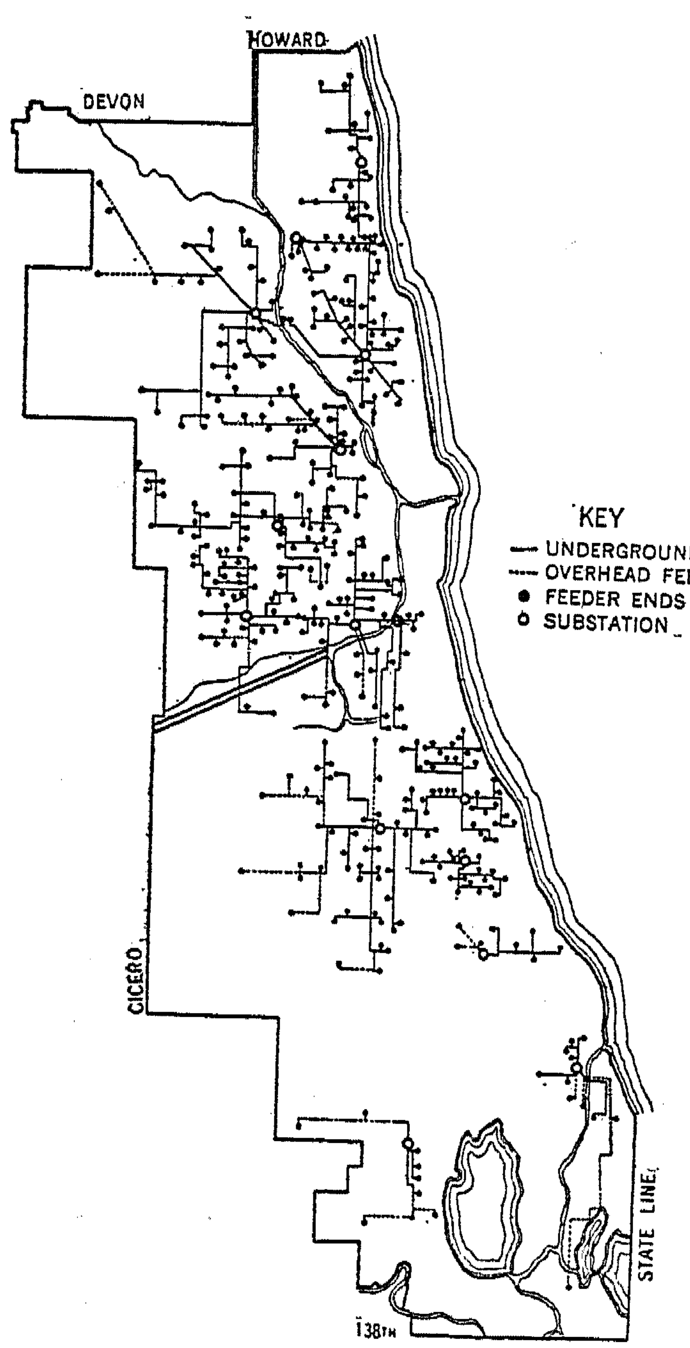


FIG. 1—MAP OF 4000-VOLT DISTRIBUTING FEEDERS IN CHICAGO

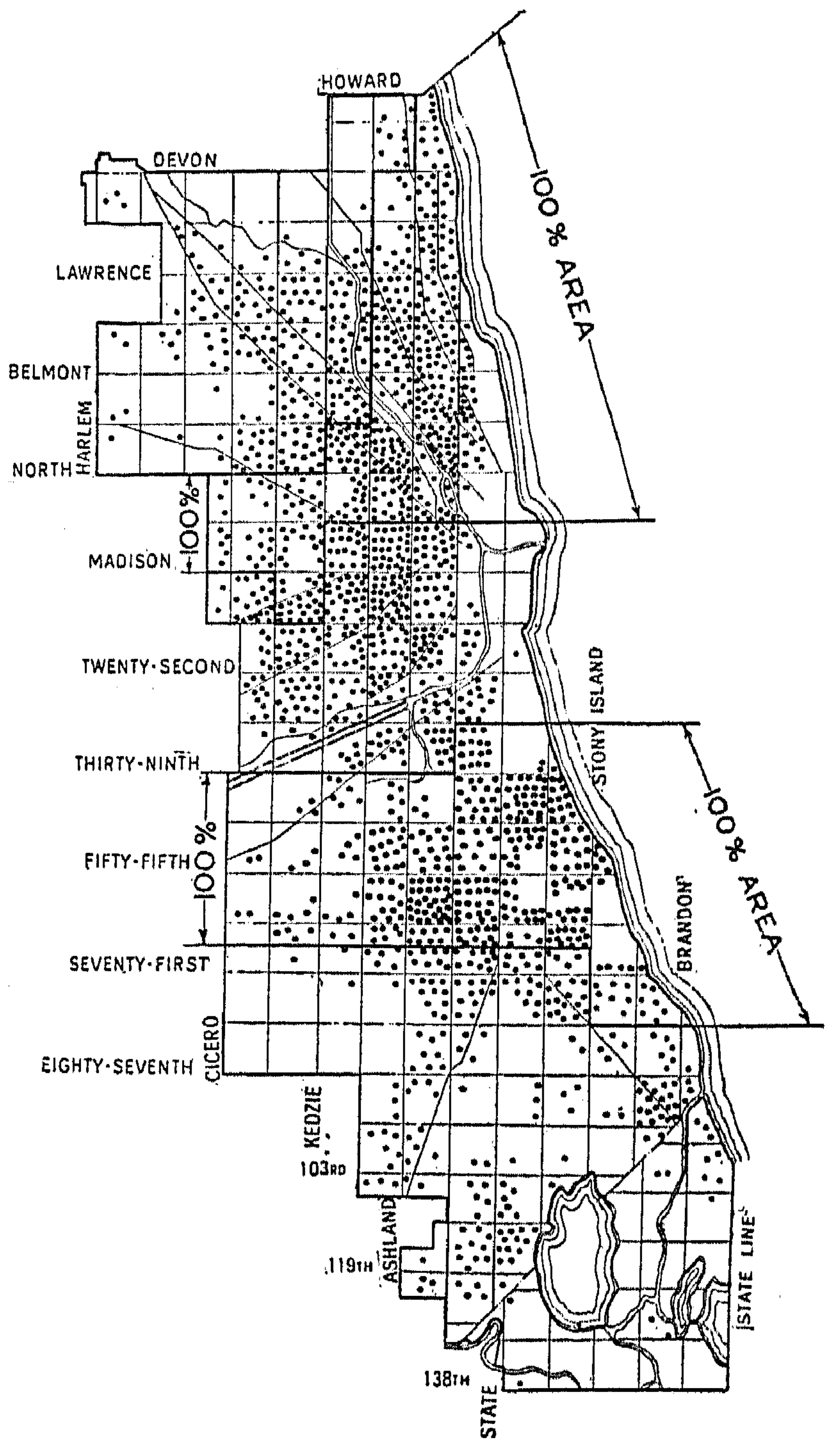


FIG. 2—TRANSFORMERS IN SERVICE IN 1915. EACH DOT REPRESENTS TEN TRANSFORMERS

II—PRELIMINARY STUDIES

As the object of the investigation was to improve the service a preliminary study was first made of all of the interruptions on the distribution system, which were classified according to their cause. This showed that transformer troubles were responsible for more interruptions to service than any other single item, and also that a large fraction of all transformer troubles

were primarily due to lightning. The need for further investigation of our lightning protection methods was, therefore, very apparent.

Upon requesting the purchasing agent to increase the size of the usual order for lightning arresters, he caused some embarrassment by inquiring what type of arrester had been shown by our experience to be best suited to our purposes. The only answer that could be given to this question was that the arresters had been selected in very much the same manner as our articles of clothing, that is, according to the type which was in fashion at the moment; and further, that the methods of installing the arresters had been such that it was quite impossible to tell from any operating records which arrester, if any, was the best. It was suggested, in the absence of definite information on the subject which would warrant a change in practise, that it seemed advisable to continue to buy arresters of each of the three types that were then in use. As it seemed quite important to determine, if possible, which was the best arrester, it was decided that such changes in the methods of installation should be made as would permit the keeping of records that would assist in securing the desired information.

III—Starting the Investigations

The first step in the investigation was to make a careful record of all transformer fuses blown by lightning during one severe storm. On the following day some of our best troublemen and linemen were sent out to examine carefully these transformers for signs of arcing which could have caused the blowing of the fuse, and in about 80 per cent of the cases the men were successful. Most of the signs indicated arcing on the primary terminal board between the terminals, or from the terminals to the cover. In a smaller number of instances, the arcing had occurred around the primary bushing either inside or outside of the transformers, or between the primary lead and the case. Investigating this matter further it was found that the repair shop had been omitting the terminal boards from all transformers which they rewound, or from those which were turned in with damaged terminal boards. Transformers altered in this manner were found to have a very excellent service record, and it therefore appeared that the advantages of the practise warranted further investigation. For this purpose one circuit was selected in 1911, to which were connected about 250 transformers, and all of the

smaller transformers were replaced by others which had their terminal boards removed. The removal of the terminal boards from the larger transformers was accomplished without removing them from the line. This work was completed so late in 1911 that no experience could be obtained during that year from the effects of lightning, and the installation remained without much change during 1912, except that care was taken to see that all additions or alterations to the circuit were made with transformers without terminal boards. No changes in the scheme of lightning protection in use previous to that time were made on this circuit, so that aside from the removal of terminal boards, this circuit was equipped in the same manner as the other circuits.

IV—Segregation of Lightning Arresters by Circuits

Previous to the time of starting these investigations, different types of arresters had been ordered in succeeding years, and the additional arresters were installed so as to protect the primary mains which had been extended during the previous year. The general plan was to locate the arresters so that there would be no transformer more than about 1000 ft. (304.8 m.) distant from the nearest arrester. Although this scheme of installation very thoroughly mixed the several types of arresters on the circuits, it was still quite possible to keep records of the failures of arresters so that it could readily be told which one was the greatest hazard to our system; but no information whatever could be secured regarding the relative merits of the several types of arresters as protective devices. In order to secure this information, the plan was therefore adopted of installing only one type of arrester on any one circuit, and a portion of the arresters were moved each year until the segregation of arresters by circuits was completed.

V—Lightning Arresters on Transformer Poles

At about the time that these investigations were started, the theory was advanced, that lightning arresters to be most effective should be on the transformer poles. For the purpose of verifying this theory, two circuits were selected early in 1912 on which there were about 300 transformers, and on each circuit an arrester was installed on the same pole with each transformer. A different type of arrester was used on the two circuits. For brevity this plan is hereafter called "100 per cent protection" and the areas are termed 100 per cent areas." This installation differed from our previous practise in that (1) the number of arresters

equaled the number of transformers instead of being only a small fraction of their number; (2) the arresters were placed on the transformer poles instead of on the line poles.

VI—Analysis of Results Obtained in 1912 and 1913

Late in the year 1912, a study was made of two of the most severe lightning storms which had occurred during the season in an endeavor to find a fair basis for the comparison of the several types of arresters. As the 100 per cent areas showed an almost entire absence of lightning trouble in these two storms, it was at first thought that the solution of the problem had been reached. To check the conclusion, a map of the city was prepared on which the 100 per cent areas were shown by colored pasters. Then the areas covered by other circuits on which there had been no trouble whatever during the same storms was shown by pasters of a different color. Upon completion of the map it was discovered that there were a number of areas, protected only by a few arresters on the line poles, which were entirely free from lightning trouble, some of them being located adjacent to the 100 per cent areas.

The records of this year, and the map with the pasters of several colors showing the circuits on which there was no trouble, indicated very plainly that it was quite impossible to definitely determine from the records, or from any subsequent examination on the ground, whether the freedom from trouble was due to the perfection of the protection or to absence of lightning, and no method has yet been discovered for overcoming the difficulty. The cause of the difficulty is the fact that, the only means available for determining the presence of lightning and its relative intensity, is by the phenomona that are to be reduced by means of the improved lightning protection; and that having installed the lightning arresters and discovered a reduction in the trouble, there is no means of telling how much trouble there would have been were the lightning arresters absent. For the same reason it is impossible to recognize a uniformly distributed lightning storm, should it occur, although such a storm would greatly simplify these investigations. An endeavor was made to secure an independent reference standard by consulting the records of the telephone company, but it was found that during the period covered by these investigations, they were rapidly replacing their overhead open wire construction with aerial cable, and that this change greatly reduced the amount of trouble on their lines during lightning storms.

As a result of the experience in 1912, it was decided that the scheme of installing the arresters on the transformer poles gave promise of beneficial results, and that in order to secure more reliable information regarding the relative merits of the several types of arresters, the 100 per cent areas should be enlarged by the addition of several circuits, each having but one type of arrester.

The information obtained from the circuit from which the terminal boards had been removed, was indefinite and not at all conclusive, due apparently, to the fact that a sufficient number of transformers were not included in the experiment. It was, therefore, decided to remove the terminal boards from a larger number of transformers, so that at the opening of the lightning season in 1913, there were a total of about 1600 transformers which had been altered in this manner.

The records obtained during 1913 demonstrated, first, that the removal of the terminal boards from transformers would eliminate about 60 per cent of the troubles due to lightning, and second, that the installation of lightning arresters on the same pole with each transformer made a very considerable further reduction in the amount of trouble from lightning, as compared with our previous practise of installing a few arresters on the line poles. (The experiments from which these results were obtained were described in further detail in a paper read by the author before the Pittsfield meeting of the A. I. E. E., May, 1914.)

As a result of the experiments with the terminal boards, it was decided that it was desirable to remove the terminal boards from all transformers which were returned to the storeroom for any reason, and orders to this effect were issued early in 1914. At about the same time it was specified that all new transformers should be without terminal boards. During the period that has elapsed since these changes in our practise were adopted, the number of transformers from which the terminal boards were removed has approximately equaled the new transformers installed on our lines, each figure being about 10 per cent per year.

VII—Ratio between Fuses Blown and Transformers Burned Out

In the investigation of the storms that occurred in 1912, it was noted that a fairly constant ratio existed between the number

of blown primary fuses and the transformers burned out by lightning. As the number of burnouts by lightning per year was approximately 125, and as the number of transformers in the 100 per cent areas was only a small fraction of the total, it was thought that more accurate data and a better comparison of the several types of arresters could be secured by using the larger number. It was, therefore, arranged to keep careful records of all primary fuses blown, as well as of the transformer burnouts. These records and the ratio of the two quantities over a period of four years is shown in Fig. 3. From this figure it is very apparent that, while the ratio may perhaps be fairly constant during one lightning season, it has decreased very considerably during the four years. It is therefore quite impossible to use the record of blown primary fuses instead of the record of burned out transformers, in the manner described, for the purpose of comparing one year's records with another. The meaning of the reduction in the ratio will be discussed in connection with the results obtained during 1915.

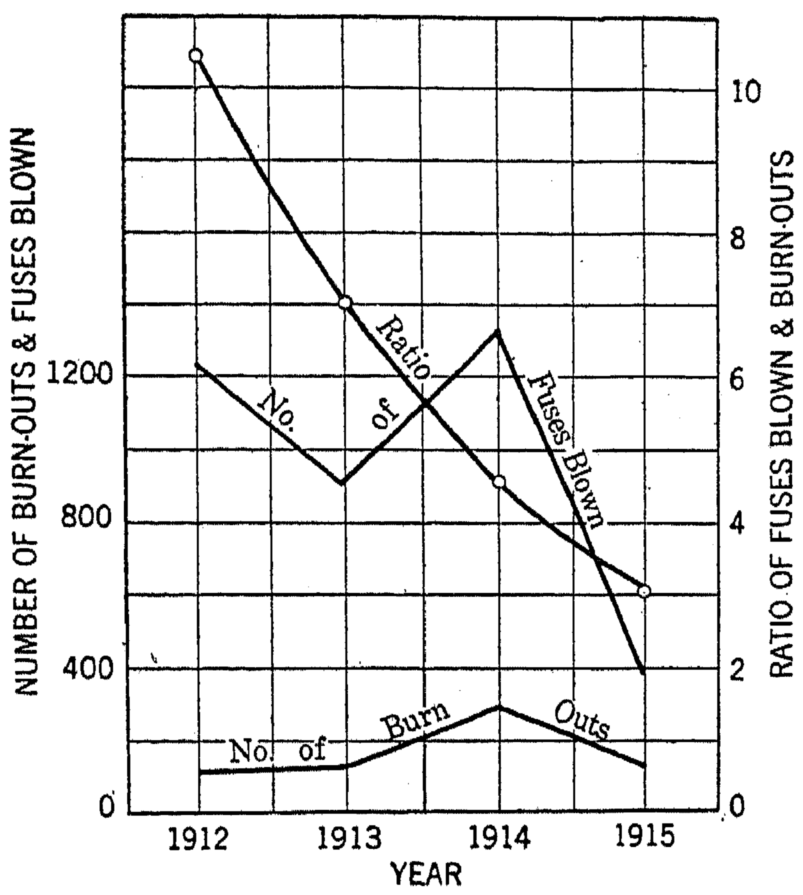


FIG. 3—RECORD FOR SEVERAL YEARS OF PRIMARY FUSES BLOWN AND TRANSFORMERS BURNED OUT BY LIGHTNING AND THEIR RATIO

VIII—GROUNDING OF TRANSFORMER CASES

The theory was also advanced that the grounding of the transformer cases would improve the lightning protection. In order to test this theory, three circuits on which there were about 600 transformers were selected, and each of the transformer cases was connected to the lightning arrester ground wire through a primary cut-out. This cut-out, with a piece of copper wire in place of the fuse, was located so that a lineman climbing the pole could readily remove the plug from the cut-out, and in this manner remove any hazard which might exist due to the grounded transformer case. Careful records were kept of this installation for a number of years. While it is entirely possible that the number of transformers included in the experiment

was inadequate for the purpose, and the records misleading due to the variableness of lightning storms, the results for three years appear to indicate that the grounding of the transformer cases has but little effect upon the efficiency of the lightning protection. As a matter of fact, there was slightly more trouble on these particular circuits than the average for other circuits, this trouble taking the nature of the burning off of the primary leads at or near the primary bushings. The area which was selected for this trial happened to be one of the older districts containing transformers which were considerably above the average age of all on the system. It is possible that the results would have been different with a modern type of transformer supplied with a larger primary bushing.

For the reasons above given, the scheme of grounding the transformer cases has been abandoned, and the ground connections installed for this purpose have been removed.

IX—Increasing the Size of Transformer Primary Fuses

Previous to the time of starting these experiments, it had been assumed that one of the principal objects of the primary fuse was to protect the transformers from overload, and the sizes of the fuses were proportioned to the capacity of the transformer. It was noted, however, that many fuses blew for which no cause could be found, and it was apparent that many fuses were blowing unnecessarily. After some discussion the old theory was abandoned, and instead a new theory was adopted, that the object of the primary fuse was to protect the service by disconnecting a defective transformer. As there were only two types of cut-outs in use, 25-ampere fuses were determined upon for use in the smaller cut-out for all transformers up to and including 10 kw., and 40-ampere fuses in the larger cut-out for transformers from 15 to 40-kw. capacity. Larger transformers are generally connected to the line without cut-outs. This rule, adopted in March 1914, was made to apply to all transformers installed, or to any fuses replaced for any reason after that date. This change in practise has resulted in a large reduction in the number of transformer fuses blown by other causes than lightning, but it is not clear that this change would have any serious effect on the blowing of fuses due to lightning, as this would mean that an arc started by the lightning would blow a five ampere fuse, for example, but that the arc might go out automatically without blowing a 25-ampere fuse. The facts

in the case are set forth, however, as it is possible that other engineers will not be entirely in accord with the author on this point.

X—Changes Made in 1914

As a result of the experiments with arresters on transformer poles, plans were adopted early in 1914, calling for some considerable additions to the 100 per cent areas for each of the several types of arresters. On account of the conditions existing at that time and the pressure of new construction work, the lightning arrester changes and additional installations were only partially completed before the opening of the lightning season. As further disturbances occurred during the middle of the summer the plans as adopted were not completely carried out until after the end of the year.

XI—Conclusions from the Records Obtained in 1914

As the changes planned for the year were only partially completed at the opening of the lightning season, and were not entirely completed until after the end of the year, the conditions were quite unfavorable for the securing of any accurate records. Although the results obtained during this year added very little to our knowledge regarding the best type of arresters, the records continued to indicate a very decided advantage for the scheme which is termed 100 per cent protection; and it further appeared that comparatively little benefit was being received from the lightning arresters installed on the line poles. As a result of this information, it was decided early in 1915 to increase the 100 per cent protection areas, (1) by moving all arresters on line poles, about 1000 in number, to the transformer poles, and (2) by installing about 3000 additional arresters. The 100 per cent areas completed previous to this time formed a broad ban across the city on the south side, in addition to a few small isolated areas on the north side. In planning the work for 1915, it was, therefore, arranged to extend the 100 per cent areas on the north side in such a manner that they would form a second band across this side of the city, and located so that it would include the most important customers. The increase year by year in the 100 per cent areas is shown in Fig. 4.

XII—Segregation of Lightning Arresters by Definite Boundaries

During the several years in which the scheme of segregating arresters by circuits had been followed, the number of primary

circuits had been increasing about 25 per cent per year. As new circuits were installed to handle the increase in load, it was necessary to move a considerable number of arresters each year in order to have only one type of arrester on each circuit. The plan was, therefore, changed so as to use streets, generally section lines, for the boundaries of the various lightning arrester districts. This change not only eliminated the annual expense

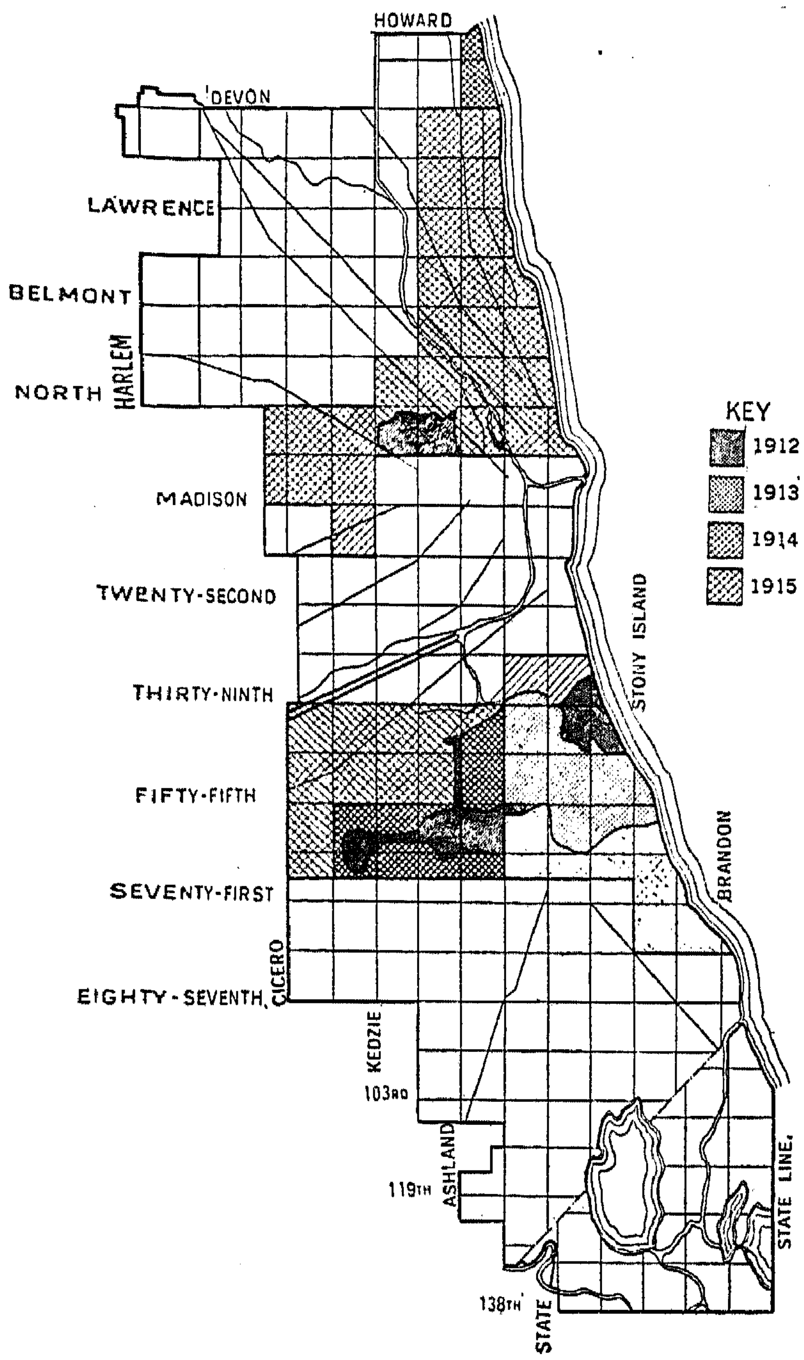


FIG. 4—MAP SHOWING 100 PER CENT AREAS FOR EACH YEAR 1912-1915

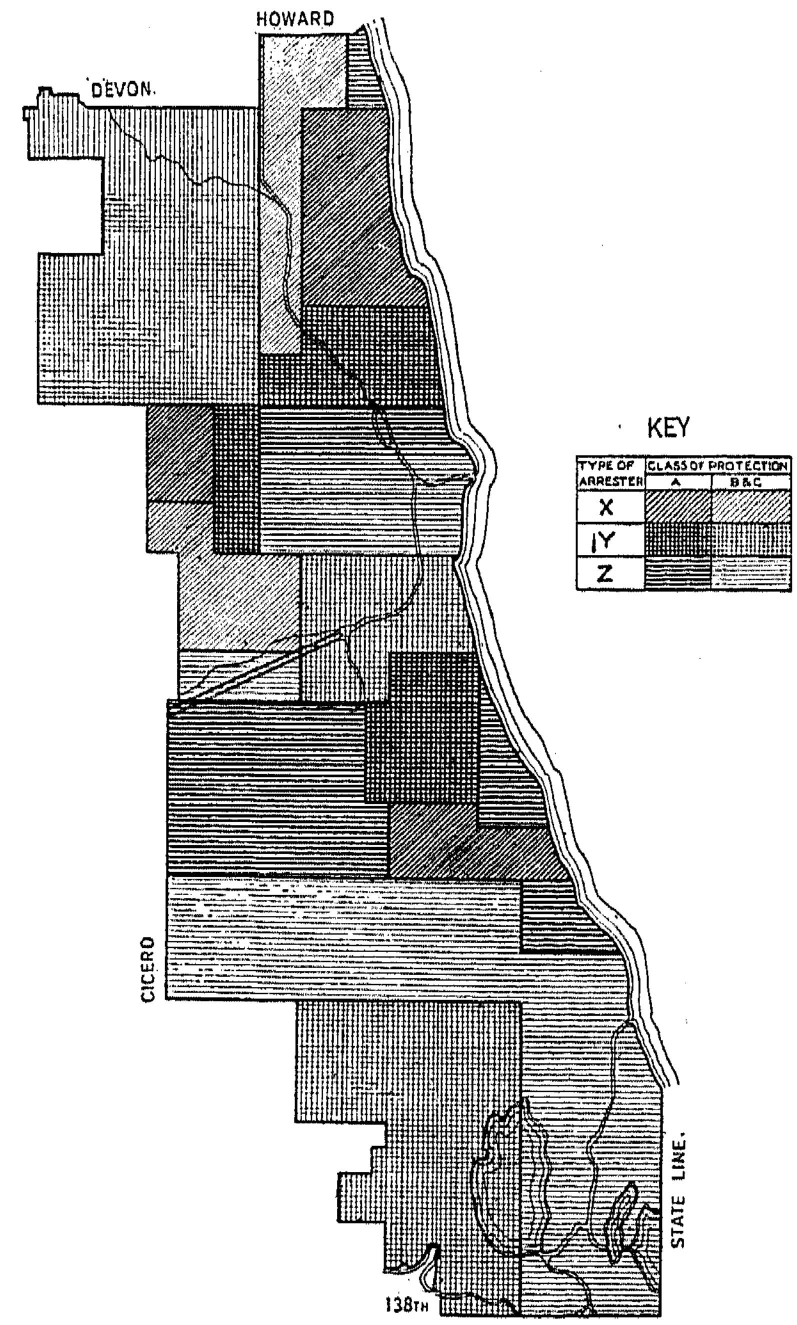


FIG. 5—MAP SHOWING SUB-DIVISION OF CITY BY TYPE OF ARRESTER AND CLASS OF PROTECTION DURING 1915

of moving arresters, which was continually increasing, but it also greatly simplified the keeping of the records and their subsequent analysis.

III—INSTALLATION OF ARRESTERS ON TRANSFORMER POLES OUTSIDE THE 100 PER CENT AREAS

As the results of the experience obtained in 1912 indicated that a considerable improvement in the service could be secured by

the installation of arresters on the transformer poles, it was decided that the extra expense of such installations was warranted in the case of important customers. Beginning in February, 1913, the plan was therefore adopted, of installing a lightning arrester on the same pole with each transformer of 15-kw. capacity or larger. In March, 1914, this rule was altered so as to include all transformers of 7.5 kw. and larger, which were thereafter installed, changed or moved. A few weeks later the rule was extended so as to include all transformers for supplying power customers, regardless of their size. In April, 1915, the rule was again altered so as to include all transformers above 3-kw. capacity.

XIV—Conditions at the Beginning of 1915

At the opening of the lightning season in 1915 there were in service three classes of protection, designated hereinafter as classes A, B and C and described as follows:

Class A. This includes the transformers which have an arrester on the same pole, and which are located in the so-called 100 per cent areas, that is, in areas in which each transformer is similiarly protected.

Class B. This includes the transformers outside of the 100 per cent areas, which are protected by arresters on the same pole, as the result of the rules adopted from time to time and set forth under heading XIII.

Class C. This includes all transformers that are not protected by arresters on the same pole, and together with the class B includes all transformers outside the 100 per cent areas.

All transformers included in this investigation come under one of the three above described classes. There are no lightning arresters installed on line poles for the protection of transformers, except in a very few isolated cases where the equipment of other companies on jointly owned transformer poles interfered with the installation of the arrester on such poles.

The manner in which the several types of arresters were distributed throughout the city is shown in Fig. 5. The letters X, Y and Z used on this map serve to designate the several types of arresters, and these letters are used throughout the various tables and discussions. The heavy shading on this map indicates the 100 per cent protection areas, and for convenience in making comparisons, the boundaries of these areas have been shown by heavy lines on other similar maps. Each of the several areas

TABLE I.

DATA ON THE SIZES OF THE TRANSFORMERS IN THE SEVERAL DISTRICTS

Area No.	Type of arrester	Class of protection	Sq. mile	No. of transformers: Below 5 kv-a.	5 to 15 kv-a.	Above 15 kv-a.	Total	Transformer per sq. mile
3	X	A	7.8	327	779	193	1299	167
8	..	..	3.0	126	138	16	280	93
16	..	..	4.0	228	344	138	710	178
..	..	..	14.8	681	1261	347	2289	155
5	Y	A	6.5	392	759	160	1311	202
7	..	..	3.0	160	280	52	492	164
13	..	..	7.0	313	489	173	975	139
			16.5	865	1528	385	2778	168
6	Z	A	4.3	132	378	80	590	137
14	..	..	9.0	281	178	47	506	56
15	..	..	3.0	100	185	129	414	138
18	..	..	2.0	127	64	3	194	97
1	..	..	0.8	38	73	6	117	130
17	..	..	7.5	420	259	35	714	95
..	..	..	26.6	1098	1137	300	2535	95
TOTAL	ALL	A	57.9	2644	3926	1032	7602	131
2	X	B	7.0	13	29	18	60	9
10	..	..	7.5	13	97	88	198	26
..	..	..	14.5	26	126	106	258	18
4	Y	B	28.5	28	67	41	136	5
11	..	..	9.2	69	180	109	358	39
20	..	..	19.5	35	54	37	126	7
21	..	..	2.0	1	3	1	5	3
..	..	..	59.2	133	304	188	625	11
9	Z	B	9.2	51	209	145	405	45
12	..	..	3.0	11	6	14	31	10
19	..	..	36.5	139	186	61	386	11
..	..	..	48.7	201	401	220	822	17
TOTAL	ALL	B	122.4	360	831	514	1705	14
2	X	C	7.0	221	129	44	394	56
10	..	..	7.5	378	392	54	824	110
..	..	..	14.5	599	521	98	1218	84
4	Y	C	28.5	926	542	36	1504	53
11	..	..	9.2	355	362	49	746	81
20	..	..	19.5	429	146	11	586	30
21	..	..	2.0	35	7	6	48	24
..	..	..	59.2	1725	1057	102	2884	49
9	Z	C	9.2	340	643	93	1076	117
12	..	..	3.0	37	23	6	66	33
19	..	..	36.5	742	300	12	1054	29
..	..	..						
..	..	..	48.7	1119	966	111	2196	45
TOTAL	ALL	C	122.4	3443	2544	311	6298	51
GRAND TOTALS		ALL	180.3	6447	7301	1857	15,605	85

was given a number and these numbers are used consistently throughout the records, but in order to avoid confusion, have been omitted from the map.

In order to assist in analyzing the results, the transformers were divided into three classes according to their size, and the number of each of the three classes in each of the areas is given in Table I. For the simplification of the calculations, the number of transformers in service on August 1st, 1915, which was approximately the middle of the lightning season, was taken as the basis of this table. From this information the percentage distribution of the transformers in the territories corresponding to each type of arrester and class of protection is shown in Table II.

TABLE II.

SUMMARY OF LIGHTNING ARRESTER DISTRICTS, SHOWING THE PERCENTAGE DISTRIBUTION OF THE TRANSFORMERS AMONG THE DISTRICTS BY GROUPS OF SIZES.

Class of protection	Type of arrester	Distribution per cent.			
		Below 5 kv-a.	5 to 15 kv-a.	Above 15 kv-a.	Total
A	X	30	15	55	100
..	Y	31	55	14	100
..	Z	43	45	12	100
..	ALL	35	51	14	100
B	X	10	49	41	100
..	Y	21	49	30	100
..	Z	24	49	27	100
..	ALL	21	49	30	100
C	X	49	43	8	100
..	Y	60	37	3	100
..	Z	51	44	5	100
..	ALL	55	40	5	100
A B C	X	35	50	15	100
..	Y	43	46	11	100
..	Z	43	45	12	100
..	ALL	41	47	12	100

XV—Records Obtained in 1915

A list of all the transformers burned out by lightning during the year with the size, area number, type of arrester and class of protection for each transformer is given in Table III.

TABLE III.
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of transformer kw.	Area No.										
1	May 3	10	9	..	..	..	..	..	..	..	..	×	Damaged
2	15	7½	2	..	×	..	..	..	..	..	..	..	Coils
		1½	2	..	..	×	..	..	..	..	..	..	"
		7½	4	..	..	×	..	..	..	..	..	..	"
		1½	4	..	..	×	..	..	..	..	..	..	"
		1	6	..	..	..	..	..	..	×	..	..	Damaged
		3	6	..	..	..	..	..	..	×	..	..	"
		7½	9	..	..	..	..	..	..	..	..	×	"
		2	9	..	..	..	..	..	..	..	..	×	"
		4	10	..	..	×	..	..	..	..	..	..	Coils
		3	10	..	..	×	..	..	..	..	..	..	"
		2	10	..	..	×	..	..	..	..	..	..	Damaged
		10	11	..	..	..	..	..	×	..	..	..	"
		1½	12	..	..	..	..	..	..	..	..	×	"
		3	14	..	..	..	..	..	..	×	..	..	Coils
		3	14	..	..	..	..	..	..	×	..	..	Damaged
		5	14	..	..	..	..	..	..	×	..	..	Coils
		15	15	..	..	..	..	..	..	×	..	..	"
		3	17	..	..	..	..	..	..	×	..	..	"
		5	17	..	..	..	..	..	..	×	..	..	Damaged
		5	17	..	..	..	..	..	..	×	..	..	Coils
		4	19	..	..	..	..	..	..	..	×	..	"
		5	20	..	..	..	..	..	×	..	..	..	Damaged
		10	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	Coils
3	June 7	10	9	..	..	..	..	..	..	..	..	×	"
		7½	6	..	..	..	..	..	..	×	..	..	Damaged
4	11	5	11	..	..	..	..	..	×	..	..	..	"
		5	9	..	..	..	..	..	..	..	×	..	Coils
5	12	4	4	..	..	..	..	..	×	..	..	..	Damaged
		1½	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	"
		4	4	..	..	..	..	..	×	..	..	..	Coils
		3	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	Damaged
		7½	4	..	..	..	..	..	×	..	..	..	"
		50	11	..	..	..	..	..	×	..	..	..	"
		2	11	..	..	..	..	..	×	..	..	..	"
		3	18	..	..	..	..	..	..	×	..	..	Coils
		2	19	..	..	..	..	..	..	..	..	×	"
		1½	19	..	..	..	..	..	..	..	..	×	"
		5	20	..	..	..	..	..	×	..	..	..	"
6	July 10	1½	19	..	..	..	..	..	..	..	..	×	Damaged
		5	19	..	..	..	..	..	..	..	..	×	"
Carried Forward				0	1	6	0	0	16	11	2	9	45

TABLE III. (*Continued*)
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of trans-former kw.	Area No.										
Brought Forward				0	1	6	0	0	16	11	2	9	45
7	July 11	1½	19	..	..	..	..	..	..	..	..	×	Coils
		2	11	..	..	..	..	..	×	..	..	..	"
8	12	3	17	..	..	..	..	..	..	×	..	..	"
9	14	7½	13	..	..	..	×	..	..	..	..	..	Damaged
		1½	19	..	..	..	..	..	..	..	..	×	Coils
		10	16	×	..	..	..	..	..	..	..	..	Damaged
10	15	5	19	..	..	..	..	..	..	..	..	×	Coils
11	18	3	10	..	..	×	..	..	..	..	..	..	"
		7½	9	..	..	..	..	..	..	..	..	×	"
		15	9	..	..	..	..	..	..	..	×	..	"
12	Aug. 14	20	3	×	..	..	..	..	..	..	..	..	Damaged
		1½	5	..	..	..	×	..	..	..	..	..	Coils
		4	4	..	..	..	..	..	×	..	..	..	"
		7½	4	..	..	..	..	..	×	..	..	..	Damaged
		2	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	"
		1½	4	..	..	..	..	..	×	..	..	..	Coils
		1	20	..	..	..	..	..	×	..	..	..	"
		2	20	..	..	..	..	..	×	..	..	..	"
13	Aug. 16	2	17	..	..	..	..	..	..	×	..	..	"
		3	19	..	..	..	..	..	..	..	..	×	"
		7½	19	..	..	..	..	..	..	..	..	×	Damaged
		4	19	..	..	..	..	..	..	..	..	×	"
		3	19	..	..	..	..	..	..	..	..	×	"
		1½	19	..	..	..	..	..	..	..	..	×	Coils
		1	19	..	..	..	..	..	..	..	..	×	Damaged
		5	19	..	..	..	..	..	..	..	..	×	"
		3	19	..	..	..	..	..	..	..	..	×	Coils
		2	19	..	..	..	..	..	..	..	..	×	Damaged
		1	19	..	..	..	..	..	..	..	..	×	Coils
		10	19	..	..	..	..	..	..	..	..	×	Damaged
		5	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	"
		2	20	..	..	..	..	..	×	..	..	..	Damaged
		1	20	..	..	..	..	..	×	..	..	..	"
		7½	20	..	..	..	..	..	×	..	..	..	Coils
		5	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		4	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	Damaged
		2	20	..	..	..	..	..	×	..	..	..	Coils
		3	20	..	..	..	..	..	×	..	..	..	"
Carried Forward				2	1	7	2	0	38	13	3	24	90

TABLE III. (*Continued*)
CLASSIFIED LIST OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915.

Type of arrester				X			Y			Z			Nature of burnout
Class of protection				A	B	C	A	B	C	A	B	C	
No. of storm	Date	Size of transformer kw.	Area No.										
Brought Forward				2	1	7	2	0	38	13	3	24	90
13	Aug. 16	1	20	..	..	..	..	..	×	..	..	..	Coils
		3	20	..	..	..	..	..	×	..	..	..	"
		7½	20	..	..	..	..	..	×	..	..	..	Damaged
		1½	20	..	..	..	..	..	×	..	..	..	"
		3	20	..	..	..	..	..	×	..	..	..	Coils
		2	20	..	..	..	..	..	×	..	..	..	"
		1½	20	..	..	..	..	..	×	..	..	..	"
		3	20	..	..	..	..	..	×	..	..	..	"
		3	20	..	..	..	..	..	×	..	..	..	"
		3	20	..	..	..	..	..	×	..	..	..	"
		4	20	..	..	..	..	..	×	..	..	..	Damaged
		7½	21	..	..	..	..	..	×	..	..	..	Coils
		2	21	..	..	..	..	..	×	..	..	..	"
14	Aug. 23	3	13	..	..	..	..	..	×	..	..	..	"
		7½	11	..	..	..	..	..	×	..	..	..	"
15	Sep. 8	1½	4	..	..	..	..	..	×	..	..	..	Damaged
		3	4	..	..	..	..	..	×	..	..	..	Coils
		2	4	..	..	..	..	..	×	..	..	..	"
		3	4	..	..	..	..	..	×	..	..	..	Damaged
		3	4	..	..	..	..	..	×	..	..	..	Coils
		1½	4	..	..	..	..	..	×	..	..	..	"
		7½	5	..	..	..	×	..	..	..	..	..	"
		2	9	..	..	..	..	..	..	..	..	×	"
		1½	10	..	..	×	..	..	..	..	..	..	"
		5	14	..	..	..	..	..	..	..	..	×	Damaged
		3	19	..	..	..	..	..	..	..	×	..	Coils
		2	19	..	..	..	..	..	..	..	..	×	"
		3	19	..	..	..	..	..	..	..	..	×	"
		2	19	..	..	..	..	..	..	..	..	×	"
16	Sep. 10	20	7	..	..	..	..	..	×	..	..	..	Damaged
		3	18	..	..	..	..	..	..	×	..	..	Coils
		5	18	..	..	..	..	..	..	×	..	..	"
		1	19	..	..	..	..	..	..	..	..	×	Damaged
GRAND TOTAL				2	1	8	3	0	60	15	4	30	73 Coils 50Damage

" Damaged " means transformer disabled by damage to leads or otherwise without injuring coils.

The location of all the transformers burned out by lightning in 1915 is shown in Fig. 6, and the fuses blown by lightning are shown in a similar way in Fig. 7. By comparing these maps with Fig. 2 it will be noted that in the 100 per cent areas where the transformers are most numerous, the burnouts and fuses blown were quite scattering, while outside of the 100 per cent areas, in which regions the transformers are not so numerous

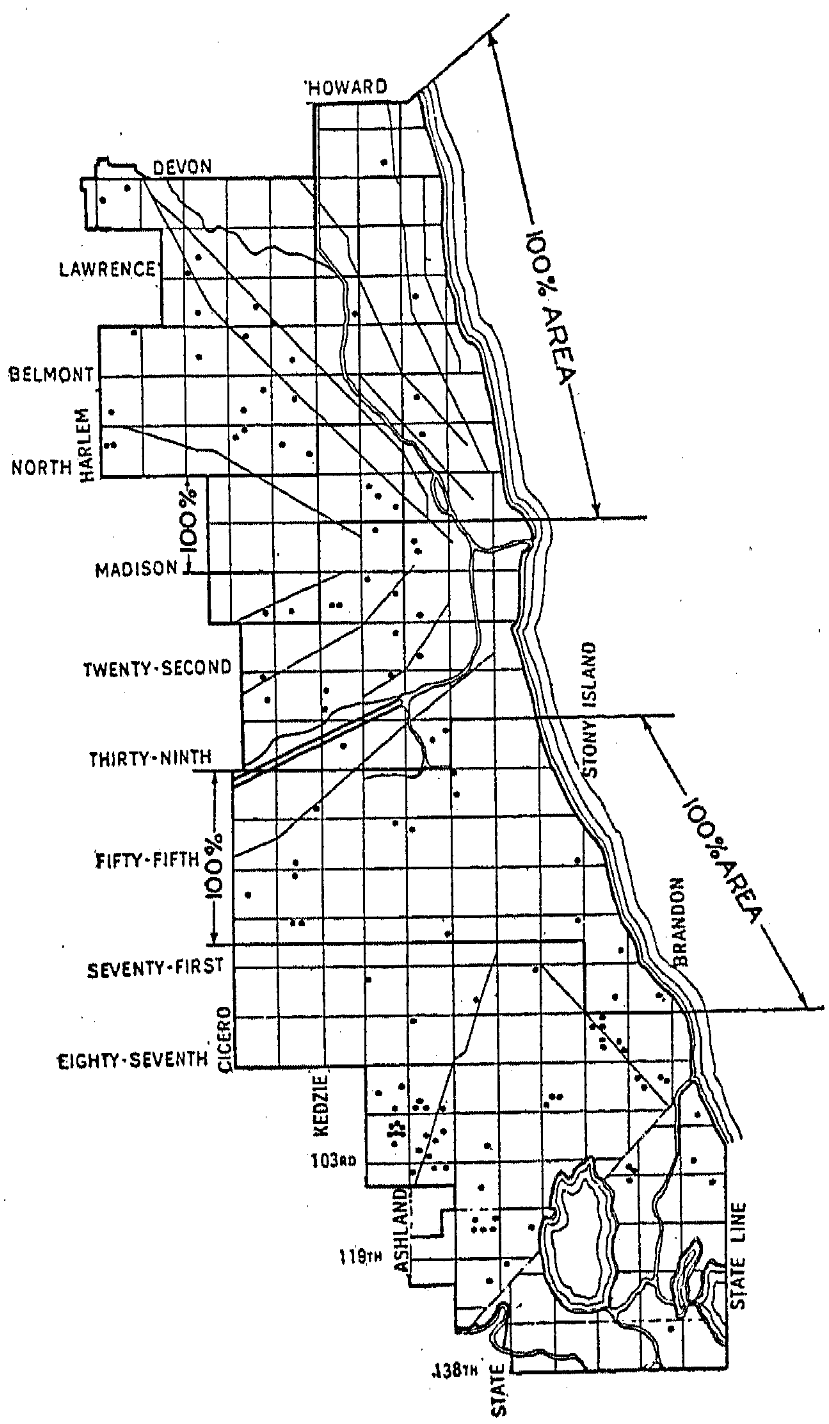


FIG. 6—TRANSFORMER BURN-OUTS DUE TO LIGHTNING 1915. EACH DOT REPRESENTS ONE BURN-OUT

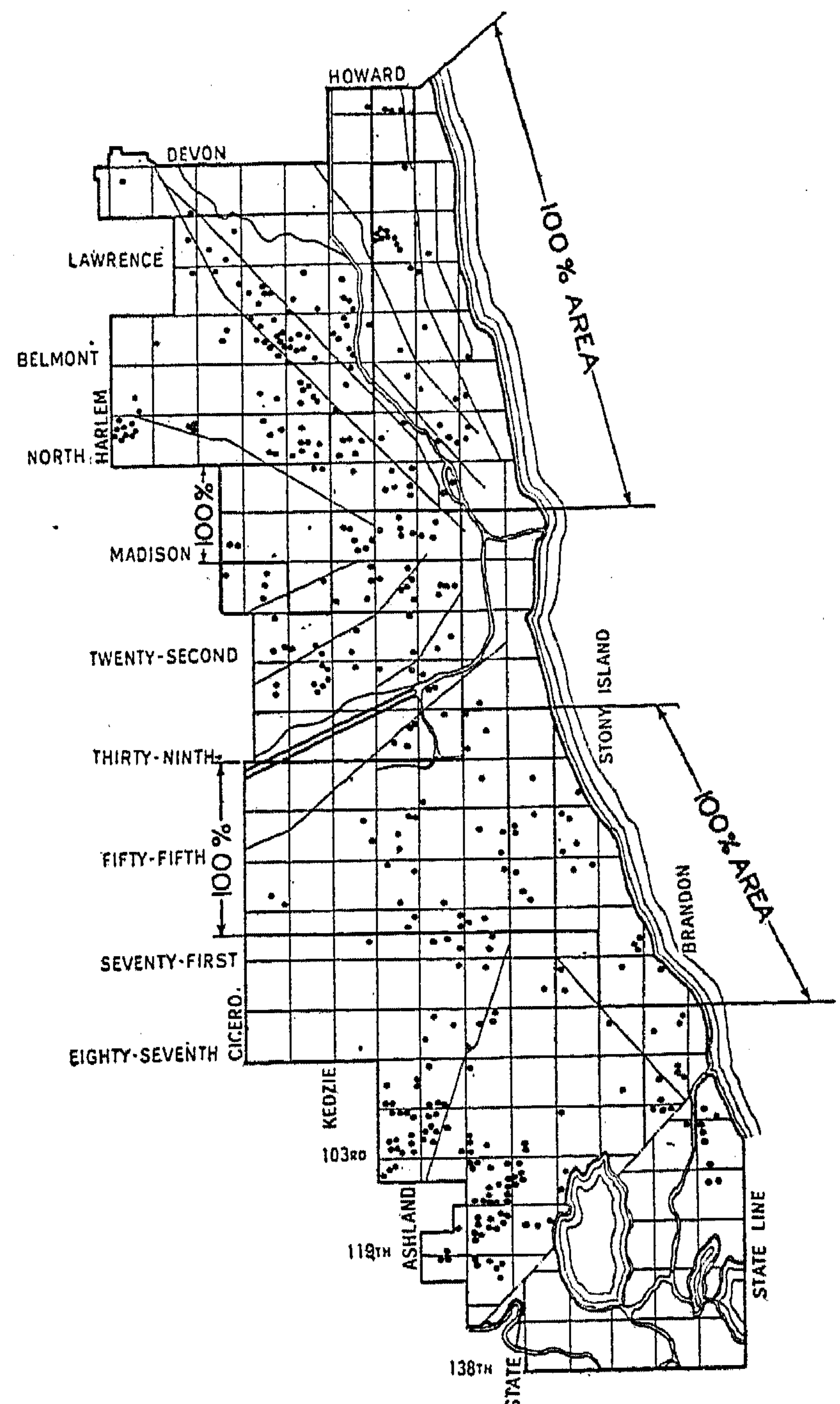
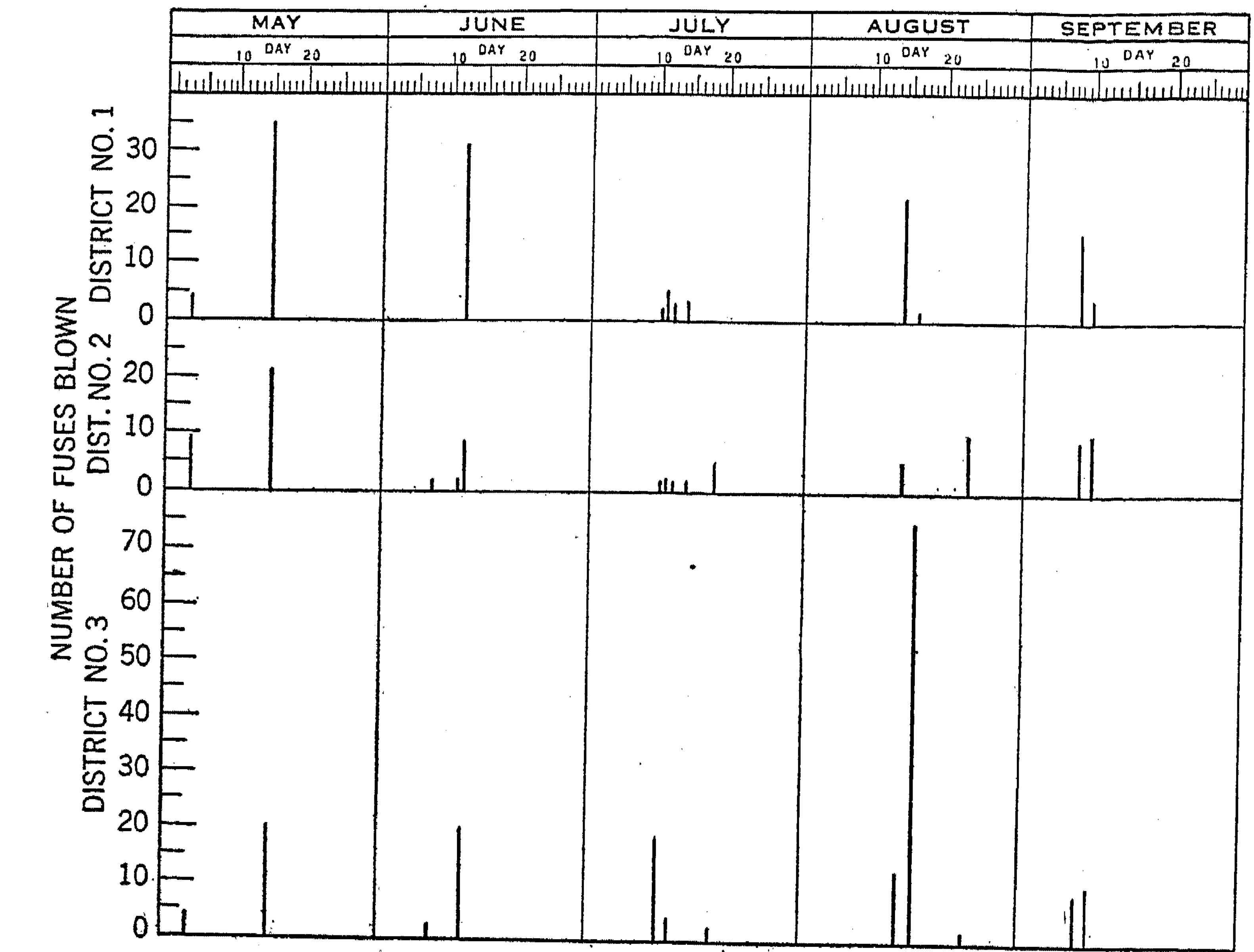


FIG. 7—FUSES BLOWN BY LIGHTNING 1915. EACH DOT REPRESENTS ONE BLOWN PRIMARY FUSE

that the burn-outs and fuses blown are more numerous, thus indicating a distinct reduction in the percentage of burn-outs and fuses blown within the 100 per cent areas.

Fig. 8 is a diagram showing the number of fuses blown and transformers burned out by lightning during the year, the arrangement being by districts. The boundaries of the districts are North Avenue and 39th Street, extending across the city from east to west. The districts are numbered in order, District

No. 1 being at the north and No. 3 at the south end of the city. This diagram shows how the various lightning storms were distributed throughout the season and among the various sections of the city. From this diagram the impression is obtained that



FUSES BLOWN IN LIGHTNING STORMS - 1915.

TRANSFORMERS BURNED OUT BY LIGHTNING - 1915.

Fig. 8

the storms of May 15th and August 16th were somewhat more erratic than the other storms and for the purpose of elucidating this point, the effects of these two storms are shown graphically in Figs. 9 and 10.

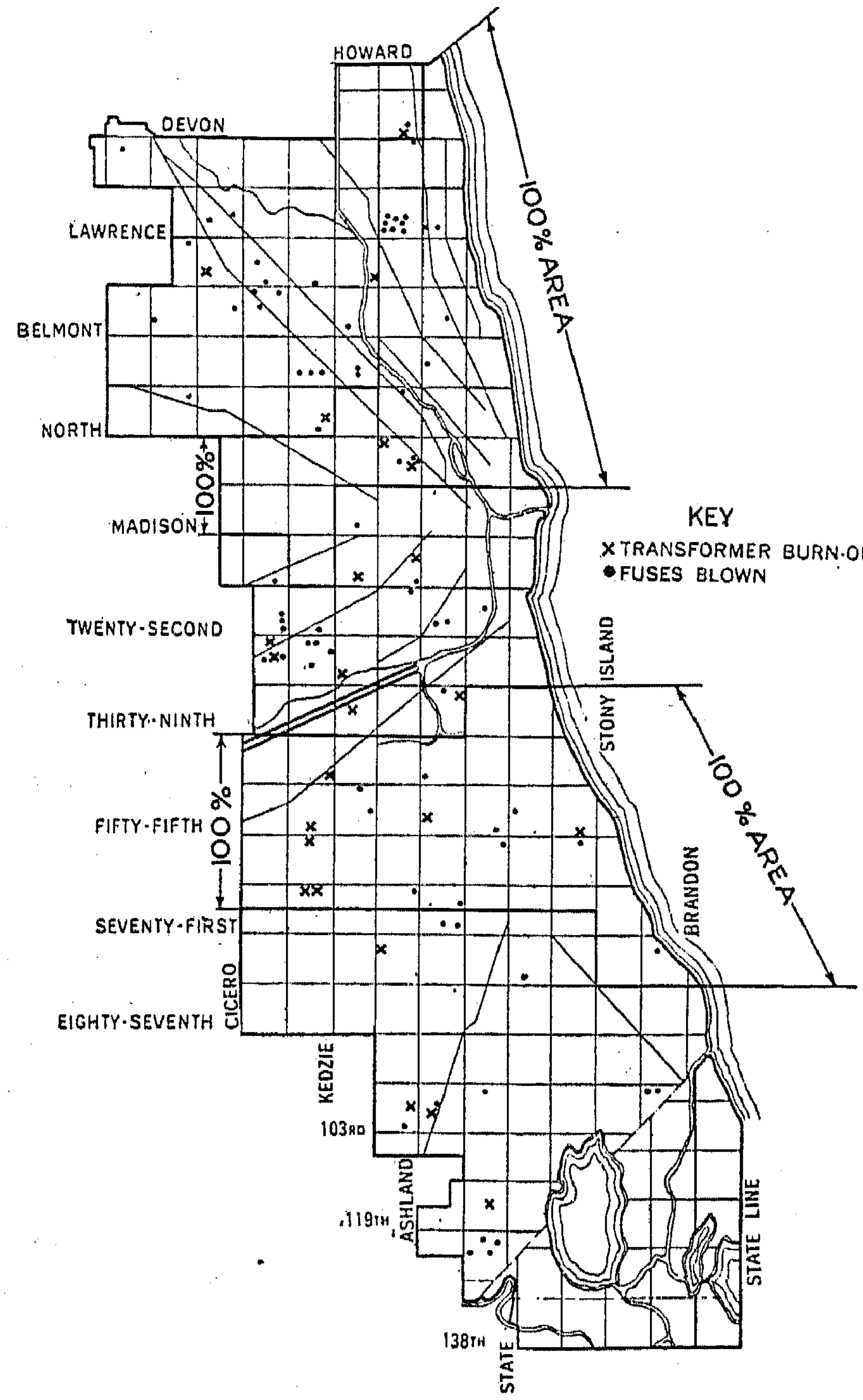


FIG. 9—TRANSFORMER BURN-OUTS AND FUSES BLOWN BY LIGHTNING STORM MAY 15, 1915

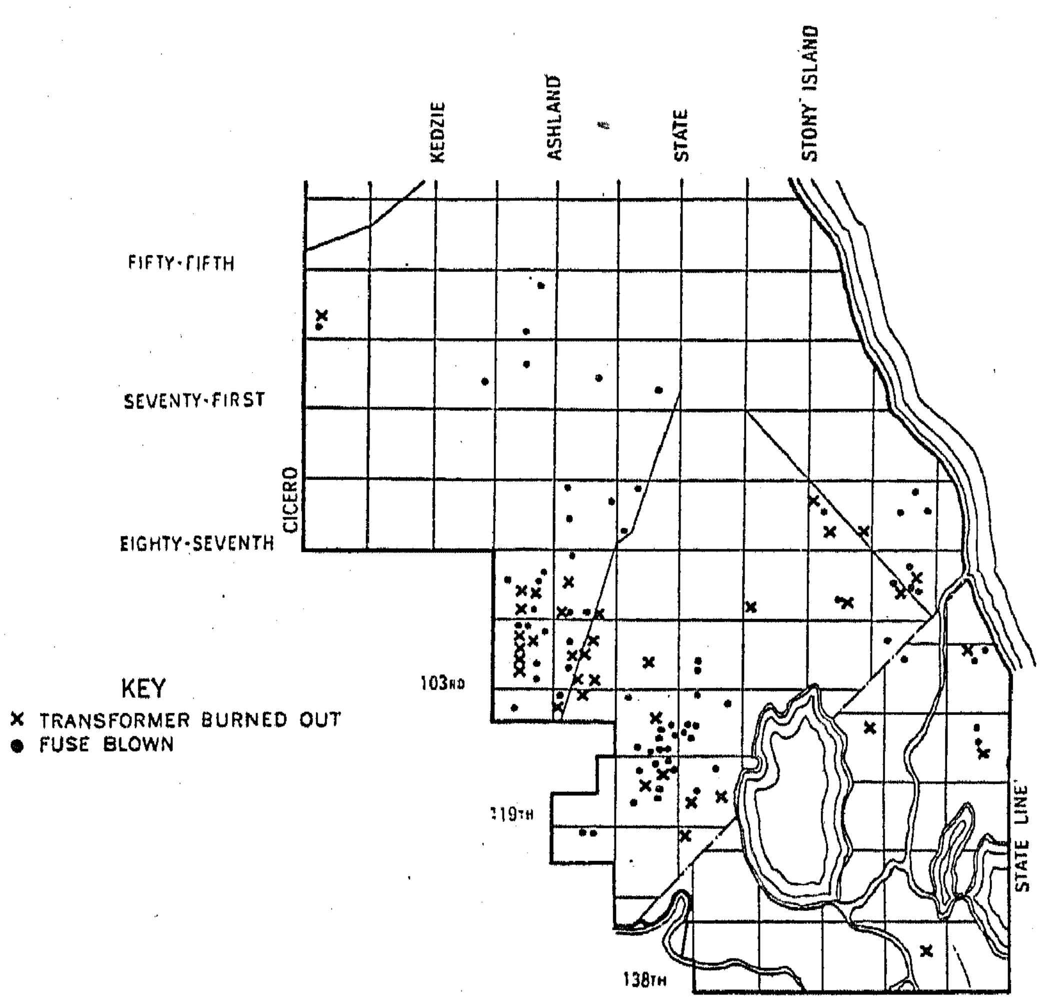


FIG. 10—LIGHTNING STORM OF AUG. 16, 1915

TABLE IV
RECORD OF TROUBLES DUE TO LIGHTNING STORMS DURING 1915.
ARRANGED BY AREAS.

Area No.	Type of arrester	Class of protection	Transformers in area	Transformers burned out		Primary fuses blown only	
				No.	Per cent	No.	Per cent
3	X	A	1299	1	0.077	17	1.31
8	..	..	280	0	0	3	1.07
16	..	..	710	1	0.141	6	0.84
..	..	..	2289	2	0.087	26	1.13
5	Y	A	1311	2	0.015	19	1.45
7	..	..	492	0	0.	5	1.02
13	..	..	975	1	0.102	11	1.13
..	..	..	2778	3	0.108	35	1.26
6	Z	A	590	3	0.51	8	1.35
14	..	..	506	3	0.59	7	1.38
15	..	..	414	1	0.24	7	1.69
18	..	..	194	3	1.54	5	2.58
1	..	..	117	0	0	0	0
17	..	..	714	5	0.70	9	1.26
..	..	..	2535	15	0.59	36	1.42
TOTAL	ALL	A	7602	20	0.26	97	1.27
2	X	B	60	1	1.67	0	0
10	..	..	198	0	0	2	1.01
..	..	..	258	1	0.39	2	0.77
4	Y	B	136	0	0	1	0.73
11	..	..	358	0	0	2	0.56
20	..	..	126	0	0	0	0
21	..	..	5	0	0	0	0
..	..	..	625	0	0	3	0.48
9	Z	B	405	2	0.49	4	0.98
12	..	..	31	0	0	0	0
19	..	..	386	2	0.52	5	1.29
..	..	..	822	4	0.49	9	1.09
TOTAL	ALL	B	1705	5	0.29	14	0.82
2	X	C	394	1	0.25	16	4.06
10	..	..	824	5	0.61	19	2.31
..	..	..	1218	6	0.49	35	2.88
4	Y	C	1504	21	1.40	72	4.78
11	..	..	746	8	1.07	16	2.14
20	..	.	586	31	5.29	88	15.01
21	..	..	48	2	4.16	0	0
..	..	..	2884	62	2.14	176	6.10
9	Z	C	1076	6	0.56	25	2.32
12	..	..	66	2	3.03	0	0
19	..	..	1054	22	2.08	35	3.32
			2196	30	1.36	60	2.73
TOTAL	ALL	C	6298	98	1.56	271	4.30
GRAND TOTALS			15,605	123	.79	382	2.44

Table IV gives a record, by areas, of the transformer trouble due to lightning, segregated by the type of arrester and class of protection. For the purpose of a better comparison the percentage figure of transformer troubles for the various classes of protection and types of arresters have been collected in Table V. Table VA shows the nature of damage to the transformers for each type of arrester and class of protection.

Tables VI and VII give a classified record, arranged by storms, of transformers burned out and primary fuses blown respectively during the year. From these tables, Figs. 11 and 12 have

TABLE V.

SUMMARY OF LIGHTNING TROUBLES DURING 1915, SHOWING THE RESULTS FOR EACH TYPE OF ARRESTER AND CLASS OF PROTECTION.

Class of protection	Type of arrester	Burn-outs per cent	Fuses blown per cent
A	X	0.087	1.13
..	Y	0.108	1.26
..	Z	0.59	1.42
	All	0.26	1.27
B	X	0.39	0.77
..	Y	0	0.48
..	Z	0.49	1.09
..	All	0.29	0.82
C	X	0.49	2.88
..	Y	2.14	6.10
..	Z	1.36	2.73
	All	1.56	4 30

been prepared, showing graphically the variations during the season of the percentage of transformers burned out and fuses blown. These tables and the figures also show plainly the erratic nature of the storms of May 15th and August 16th. It will be noted, for example, that 60 per cent of the total number of burn-outs for type *Z* arrester and class A protection occurred on May 15th, although the total number of transformers burned out on this day was only 20 per cent of the total occurring dur-the season.

Table VIII gives data regarding the transformer troubles for each size of transformer. These troubles have been further

TABLE NO. 5-A

TRANSFORMERS BURNED OUT BY LIGHTNING DURING 1915 CLASSIFIED BY TYPE OF PROTECTION AND EXTENT OF DAMAGE.

	No. of burn-outs							
Class of protection	A and B				C			All
Type of arrester	X	Y	Z	Total	X	Y	Z	Total
Coils burned out..........	1	3	16	20	5	40	20	65
Transformers put out of commission, but coils O.K.	2	0	3	5	1	22	10	33
Totals...............	3	3	19	25	6	62	30	98

TABLE VI.

RECORD OF TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915, ARRANGED BY STORMS.

Type of arrester		X			Y			Z			TOTALS			Grand Total
Class of protection		A	B	C	A	B	C	A	B	C	A	B	C	
No. of storm	Date													
1	May 3	0	0	0	0	0	0	0	0	1	0	0	1	1
2	15*	0	1	6	0	0	4	9	1	3	9	2	13	24
3	June 7	0	0	0	0	0	0	1	0	1	1	0	1	2
4	11	0	0	0	0	0	1	0	1	0	0	1	1	2
5	12	0	0	0	0	0	11	1	0	2	1	0	13	14
6	July 10	0	0	0	0	0	0	0	0	2	0	0	2	2
7	11	0	0	0	0	0	1	0	0	1	0	0	2	2
8	12	0	0	0	0	0	0	1	0	0	1	0	0	1
9	14	1	0	0	1	0	0	0	0	1	2	0	1	3
10	15	0	0	0	0	0	0	0	0	1	0	0	1	1
11	18	0	0	1	0	0	0	0	1	1	0	1	2	3
12	Aug. 14	1	0	0	1	0	7	0	0	0	2	0	7	9
13	16	0	0	0	0	0	27	1	0	11	1	0	38	39
14	23	0	0	0	0	0	2	0	0	0	0	0	2	2
15	Sep. 8	0	0	1	1	0	6	0	1	5	1	1	12	14
16	10	0	0	0	0	0	1	2	0	1	2	0	2	4
	TOTALS	2	1	8	3	0	60	15	4	30	20	5	98	123

*The two storms occurring on May 15th, one in the early morning and one in the late afternoon, have been classed as one storm, on account of the impossibility of making an accurate separation.

segregated in Tables IX and X so as to show the variation in the percentage of trouble in the transformers supplied by various manufacturers. The percentage figures from Table VIII have been plotted in Fig. 13, and there has been added, for the purpose of comparison, the corresponding information from the records of 1913.

TABLE VII.

RECORD OF TRANSFORMER PRIMARY FUSES BLOWN BY LIGHTNING IN 1915, ARRANGED BY STORMS.

Type of arrester		X			Y			Z			Totals			Grand Total
Class of protection		A	B	C	A	B	C	A	B	C	A	B	C	
No. of storm	Date													
1	May 3	2	0	1	3	0	4	1	0	7	6	0	12	18
2	15*	11	0	14	5	0	30	8	1	8	24	1	52	77
3	June 7	0	0	0	0	0	0	1	1	0	1	1	0	2
4	11	1	0	0	0	0	0	0	0	0	1	0	0	1
5	12	3	0	9	8	1	26	10	0	3	21	1	38	60
6	July 10	3	0	0	0	0	16	0	0	1	3	0	17	20
7	11	0	0	1	1	0	3	0	0	2	1	0	6	7
8	12	0	0	0	0	0	7	0	0	1	0	0	8	8
9	14	0	0	1	3	0	0	0	0	0	3	0	1	4
10	15	0	0	0	0	0	0	0	0	0	0	0	0	0
11	18	0	0	1	2	0	0	0	0	3	2	0	4	6
12	Aug. 14	4	0	3	4	1	26	1	0	0	9	1	29	39
13	16	0	0	0	1	0	42	4	2	26	5	2	68	75
14	23	0	1	2	0	0	4	1	0	2	1	1	8	10
15	Sep. 8	2	0	2	3	0	14	3	3	4	8	3	20	31
16	10	0	1	1	5	1	4	7	2	3	12	4	8	24
	Totals	26	2	35	35	3	176	27	9	60	97	14	271	382

*The two storms occurring on May 15th, one in the early morning and one in the late afternoon, have been classed as one storm, on account of the impossibility of making an accurate separation.

Fig. 14 shows the ratio of primary fuses blown to transformer burn-outs during the year for each class of protection. The variations in the ratio for all classes of protection are shown in Fig. 15 to which has also been added, for comparison, similar information for 1913.

XVI—Comments on the Analysis of the Records

In attempting to analyze the records and to discover the funda mental principles of lightning protection, not only is one con-

fronted by records which are incomplete and inaccurate due to the errors which naturally creep into any records that are collected from so many sources, and through so many individuals but there are a large number of variables affecting the amount of trouble due to lightning, which might be roughly outlined as follows:

1. The percentage of terminal boards removed.
2. The ratio of lightning arresters to transformers.

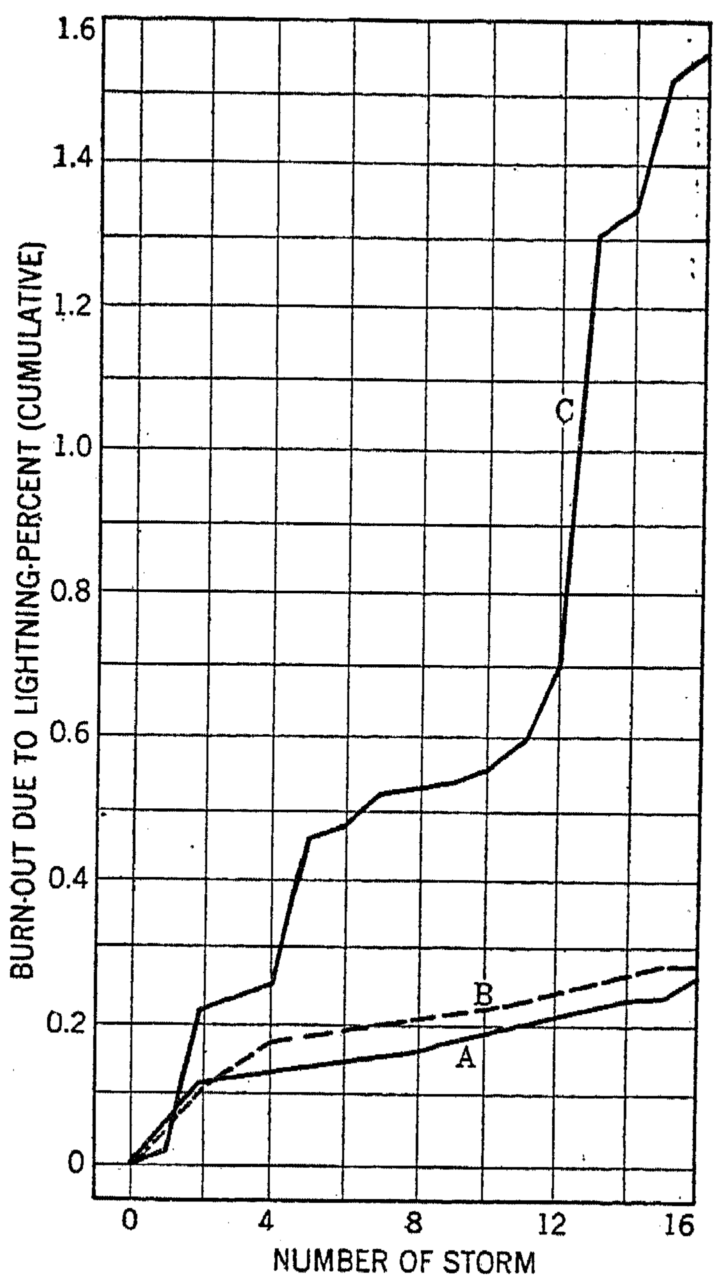


Fig. 11—Graphic Log of Transformers Burned Out by Lightning in 1915, Subdivided by Classes of Protection

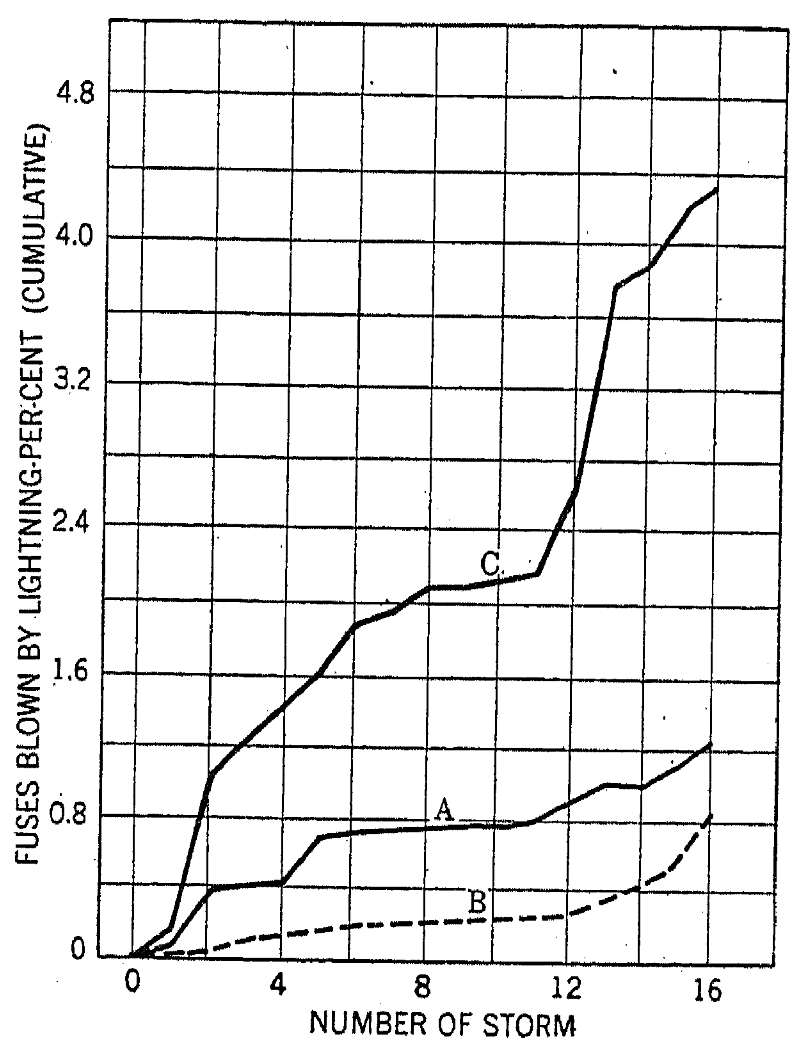


Fig. 12—Graphic Log of Fuses Blown by Lightning in 1915, Subdivided by Classes of Protection

3. Location of the lightning arresters, *i.e.*, whether on the line poles or transformer poles.
4. Density of the arresters, *i.e.*, the number per square mile or per mile of line.
5. The maker of the transformer.
6. The variations in the distribution and intensity of the lightning.

In general the variations of the lightning itself overshadow the rest of the variables so that the latter are sometimes quite insigni-

ficant in comparison. In other cases the variations in the variables apparently oppose each other, or perhaps act together in such a way that their effect becomes very obscure.

The large variations due to the lightning itself, may be noted in any of the records which give percentage figures for the various numbered areas, and from these records we gather that it is quite unsafe to assume that the record for any particular area correctly represents the average conditions throughout the city. The most representative figures are those which are obtained

TABLE VIII.
RECORD OF TRANSFORMER TROUBLES CAUSED BY LIGHTNING IN 1915, FOR EACH SIZE OF TRANSFORMER

Size kw.	Transformers in service August 1st, 1915.	Burned out		Fuses blown	
		No.	Per cent	No.	Per cent
1	407	7	1.72	22	5.41
1.5	1,090	23	2.11	61	5.59
2	1,103	21	1.90	51	4.61
3	2,381	25	1.05	51	2.14
4	1,149	8	0.70	20	1.74
5	2,075	14	0.67	54	2.60
7.5	2,304	14	0.61	61	2.64
10	1,852	6	0.32	35	1.89
15	1,320	2	0.15	16	1.21
20	648	2	0.31	2	0.31
25	451	0	0	3	0.67
30	186	0	0	1	0.54
40	152	0	0	1	0.66
50	243	1	0.41	4	1.65
75	114	0	0	0	0
100	117	0	0	0	0
150	12	0	0	0	0
250	1	0	0	0	0
TOTALS	15,605	23	0.78	382	2.44

from the combined experience in a number of areas. In some cases this is not possible, and in those particular cases the attempt to plot the relation between any quantity and the effects of the lightning are quite dissappointing.

It is also to be noted that in attempting to find the relation between any one variable and the lightning effects, the other variables must for the moment be assumed as constant. The records show that this last assumption is always in error to a greater or less extent. Sometimes the variations from the assumption is not sufficient to seriously affect the records, but in other

TABLE IX.

TRANSFORMER BURNOUTS DUE TO LIGHTNING DURING 1915, FOR EACH SIZE AND MAKE OF TRANSFORMER PER CENT

Maker	A	B	C	D	E	Total
Size kw.						
1	0	1.55	....	....	16.65	1.72
1.5	1.43	1.17	1.40	0	10.48	2.11
2	1.11	1.73	2.61	0	7.41	1.90
3	0.29	0.96	0.97	0	6.06	1.05
4	0	0.65	1.00	6.67	....	0.70
5	0	0.83	0.46	0	0	0.67
7.5	1.04	0.39	0	0	2.20	0.61
10	0.45	0	1.74	0	0.84	0.32
15	0	0.13	0.72	0	0	0.15
20	1.89	0	0	16.65	0	0.31
25	0	0	0	....	0	0
30	0	0	0	0	0	0
40	0	0	0	0	0	0
50	0	0	0	9.09	0	0
TOTALS	0.51	0.66	0.81	1.47	1.69	0.78

TABLE X.

TRANSFORMER FUSES BLOWN BY LIGHTNING FOR EACH SIZE AND MAKE OF TRANSFORMER DURING 1915

Maker	A	B	C	D	E	Total
Size kw.						
1	12.5	5.5	....	0	0	5.41
1.5	5.7	5.8	4.9	....	4.8	5.59
2	4.5	4.4	7.8	0	0	4.61
3	1.4	2.2	3.5	0	1.0	2.14
4	1.8	1.7	2.0	0	....	1.74
5	3.3	2.3	3.2	0	7.5	2.60
7.5	2.1	2.3	5.6	4.0	2.6	2.64
10	2.3	1.5	4.4	5.0	1.7	1.89
15	1.6	1.3	2.9	0	0	1.21
20	1.9	0.3	0	0	0	0.31
25	0	0.8	0	....	0	0.67
30	0	1.2	0	0	0	0.54
40	0	1.1	0	0	0	0.66
50	0	2.5	0	0	0	1.65
TOTALS	2.34	1.33	3.55	1.47	1.33	2.44

NOTE: The letters used to represent the maker, correspond with those used in Table IX

cases the variations are apparently so great that it is quite impossible to draw any conclusions from the results obtained, except in a very general way.

XVII—Reduction in the Ratio of Primary Fuses Blown to Transformers Burned Out

While the number of primary fuses blown and the burnouts due to lightning during the past four years have varied over

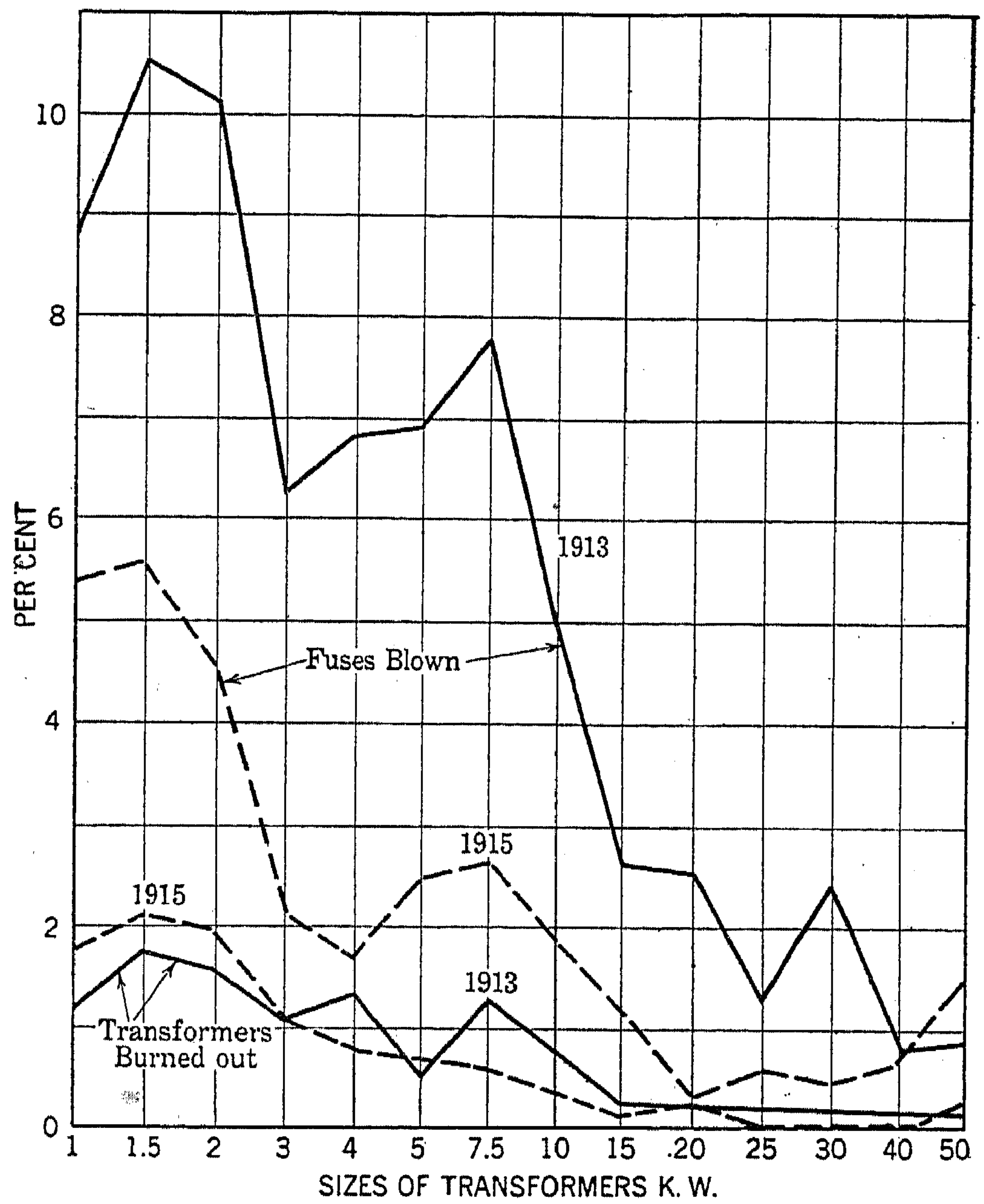


Fig. 13—Comparative Records of Primary Fuses Blown and Transformers Burned Out by Lightning in 1913 and 1915

rather wide limits from year to year as shown in Fig. 3, the ratio between these two quantities during the same period has been decreasing along a very regular curve, indicating the existence of some law or progressive change connecting these two quantities. For the purpose of securing information on this point, Table XI has been prepared showing the ratio in question for the several classes of protection during 1915. This table shows that the ratio is smaller for the class B and C protection than for class A. This ratio, being the larger for the best class

of protection, indicates that the other variables have a greater effect on this ratio than the lightning arresters.

Fig. 16, showing the reduction in the percentage of terminal boards and in the percentage of fuses blown by lightning, indicates that there must be some close relation between these two quantities as indicated by the fact that the curves are, in general parallel. (In this figure the values for transformers above 15-kw. capacity have been omitted, as not more than four fuses of

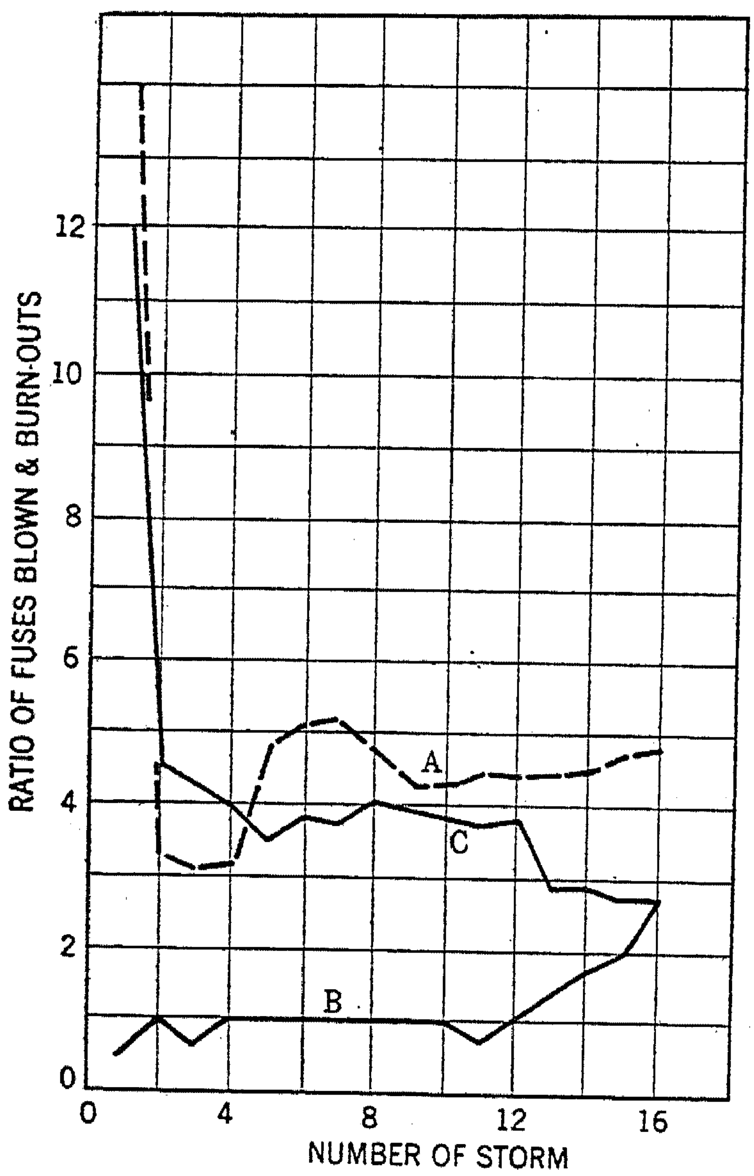


FIG. 14—DIAGRAM SHOWING RATIO OF FUSES BLOWN TO TRANSFORMERS BURNED OUT BY LIGHTNING IN 1915 FOR VARIOUS CLASSES OF PROTECTION

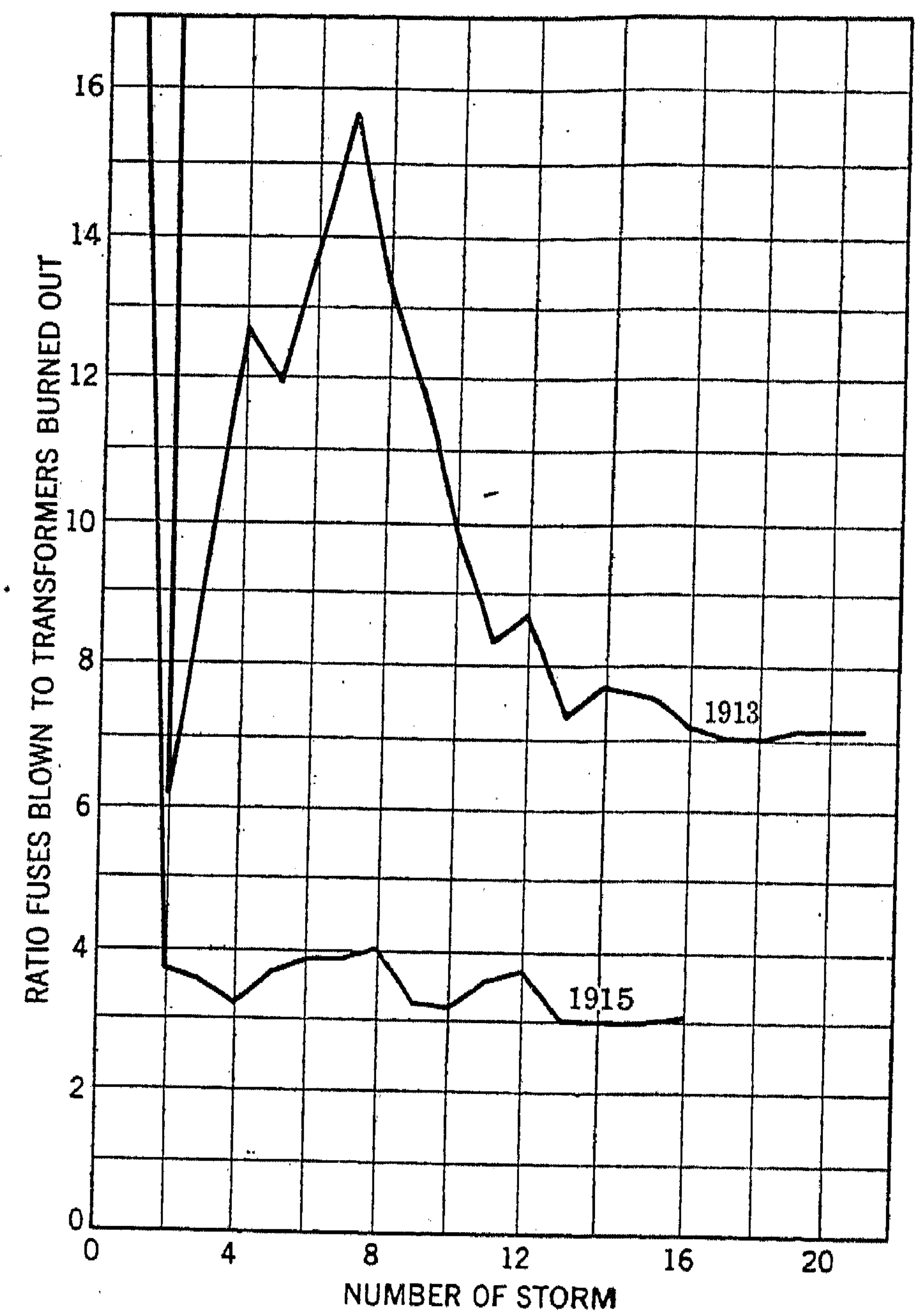


FIG. 15—DIAGRAM SHOWING RATIO OF PRIMARY FUSES BLOWN TO TRANSFORMERS BURNED OUT BY LIGHTNING IN 1913 AND 1915

any of these sizes were blown during the year.) In order to determine the relation between the removal of the terminal boards and the reduction in the fuses blown, these two quantities have been plotted directly in Fig. 17. After making due allowance for the various inaccuracies in the assumptions and conditions, the points from Fig. 16 when plotted in this manner show that the relation between the two quantities is a function represented by a straight line passing through the origin, or in other

words, that the percentage reduction in fuses blown is directly proportional to the percentage of terminal boards removed.

Upon examining this line more carefully, an apparent inconsistency is noted in that the removal of 30 per cent of the terminal boards caused a reduction of 59 per cent in the fuses blown by lightning. Such a result could occur only if some

TABLE XI.

EFFECT OF CLASS OF PROTECTION ON RATIO OF FUSES BLOWN TO TRANSFORMERS BURNED OUT IN 1915.

Class of protection	A Primary fuses blown	B Transformers burned out	Ratio $\frac{A}{B}$
A	97	20	4.85
B	14	5	2.80
C	271	98	2.75

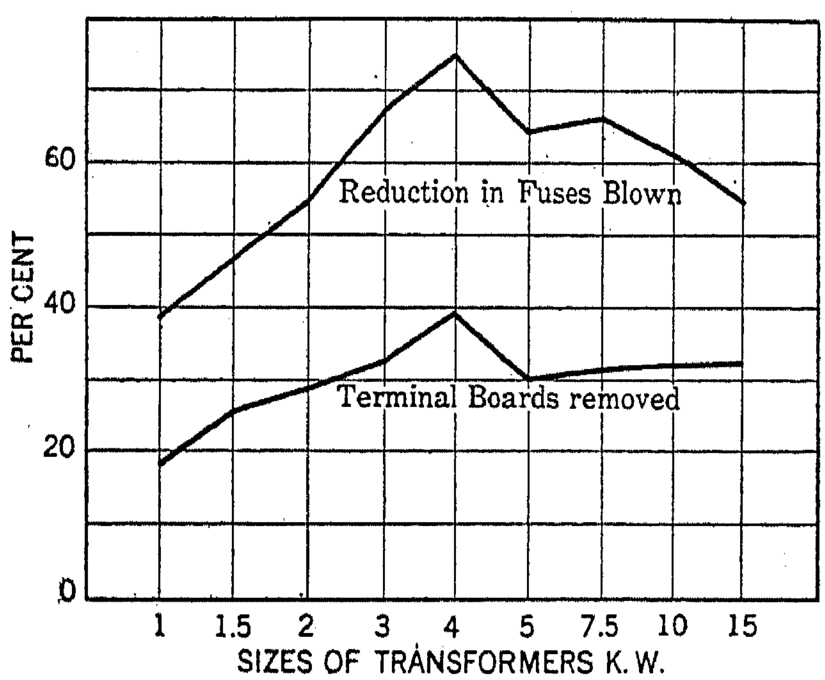


FIG. 16 — DIAGRAM SHOWING EFFECT OF REMOVAL OF TERMINAL BOARDS FOR TWO YEARS ON PERCENTAGE OF FUSES BLOWN BY LIGHTNING

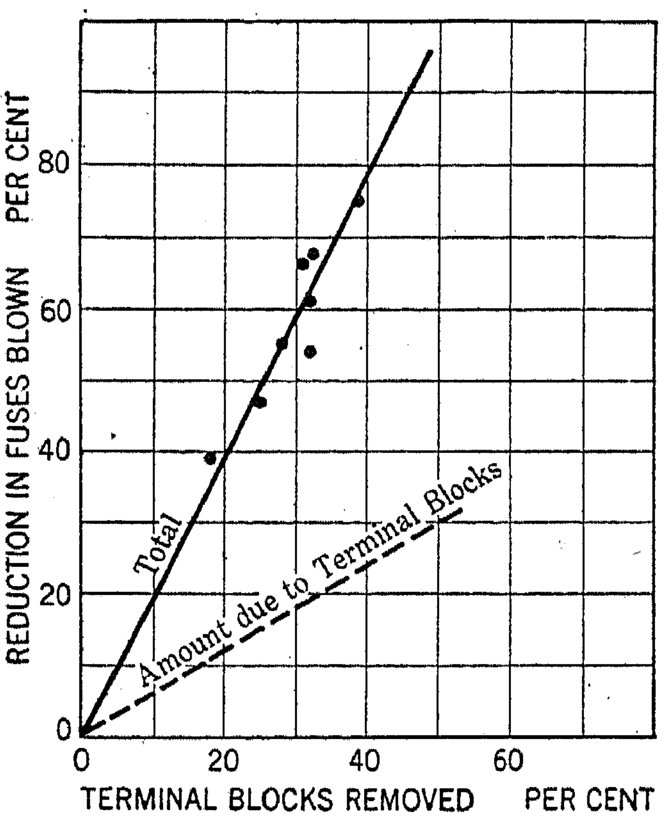


FIG. 17—DIAGRAM SHOWING RELATION BETWEEN REMOVAL OF TERMINAL BOARDS AND REDUCTION IN BLOWING OF PRIMARY FUSES

scheme of selection were practised in the removal of the primary terminal boards, so that the ones most likely to cause trouble were the ones to be removed; but no such scheme of selection has been in use, and instead, all of the transformers passing

through the storeroom have had their terminal boards removed before again being sent out on the line.

In the paper by the author read at Pittsfield in 1914, and previously referred to, it was stated that the removal of all of the terminal boards from the transformers in a given area eliminated about 60 per cent of the transformer troubles caused by lightning. Assuming for the moment that this figure is correct, then we might reasonably conclude that the removal of 30 per cent of the terminal boards should reduce the troubles by 30 per cent of 60 per cent, or 18 per cent. The dash line in Fig. 17 shows this value. If we assume that this line is correctly drawn, then the percentage reduction in fuses blown between the dash line and the full line must be due to other causes.

During the same period, that is, between 1913 and 1915, the lightning protection of the system has been improved, (1) by increasing the number of arresters on the line, and (2) by moving the arresters from the line poles to the transformer poles. It is not thought that any of the other changes made during this period could have seriously affected the ratio. The difference between the dash line and the full line on Fig. 17, apparently, must be ascribed to the improvement in the lightning protection secured by the lightning arresters. The records available do not permit of an exact determination of the benefits derived from increasing the number of arresters as distinguished from the benefits obtained by moving the arresters from the line poles to the transformer poles, but from all of the information obtainable, some of which is set forth under a later heading in this paper, it is estimated that the reduction of 59 per cent in fuses blown corresponding to the removal of 30 per cent of the terminal boards can be allotted to the several contributing causes about as follows:

	Per cent	Per cent of total
Removal of terminal boards	18	30
Increasing the ratio of arresters to transformers	10	20
Moving arresters from line poles to transformer poles	31	50
	59	100

If this estimate is approximately correct, it means that the amount of trouble from lightning, on a system with all the terminal boards removed and with lightning arresters equal in number to the transformers and installed on the line poles,

would be reduced about one-half by moving the lightning arresters from the line poles to the transformer poles.

A careful investigation was made of transformer fuses blown in 1915, in order to determine how much improvement was due to the removal of the terminal boards only and to the installation of the arresters independent of the removal of terminal boards. If we start with transformers having terminal boards above oil and without lightning arresters on the same pole, then the improvement obtained by each of the several steps, as indicated by our experience in 1915, is as follows:

		Improvement
1.	Removal of terminal boards only............	50%
2.	Installation of lightning arresters on the transformer poles only........................	85%
3.	Removing terminal boards from transformers already protected by an arrester on the same pole............................	30%
4.	Removing terminal boards and installing arresters on the same pole................	90%

XVIII—Comparison of Several Classes of Protection

Class A and B protection both include transformers having lightning arresters on the same pole. They differ, however, in that class A transformers are all in a segregated area in which each transformer is similarly protected, while the transformers of the class B protection may be surrounded by other transformers of class C protection, that is, without arresters on the same poles. Fig. 11 indicates that according to the record of burn-outs, class A is appreciably better than class B. Fig. 12, showing the record of fuses blown, indicates that class B is considerably better than class A. This latter difference is probably accounted for largely by the rule above mentioned, according to which transformers above 3-kw. capacity were protected by an arrester on the same pole, while the smaller transformers were not so protected. Class B protection, therefore, consists of a selected lot of transformers from which the smaller, or more vulnerable sizes are largely excluded. This is shown by Table II, which indicates that 21 per cent of the transformers in class B protection were below five kw., while for class A protection this figure was 35 per cent.

If the improvement of class A protection over class B, as indicated in Fig. 11, correctly represents their relative merits, then these conditions must be due to the larger number of arresters

per square mile, or per mile of line, for class A protection as compared with class B. A reference to Table I shows that there are about ten times as many transformers per square mile for class A protection as for class B. These figures indicate that the installation of an arrester on a transformer pole does not give perfect or complete protection, but that the protection is considerably improved by other arresters on neighboring poles. This means that widely separated transformers along a long line, or isolated at the end of a line, if supplying important service

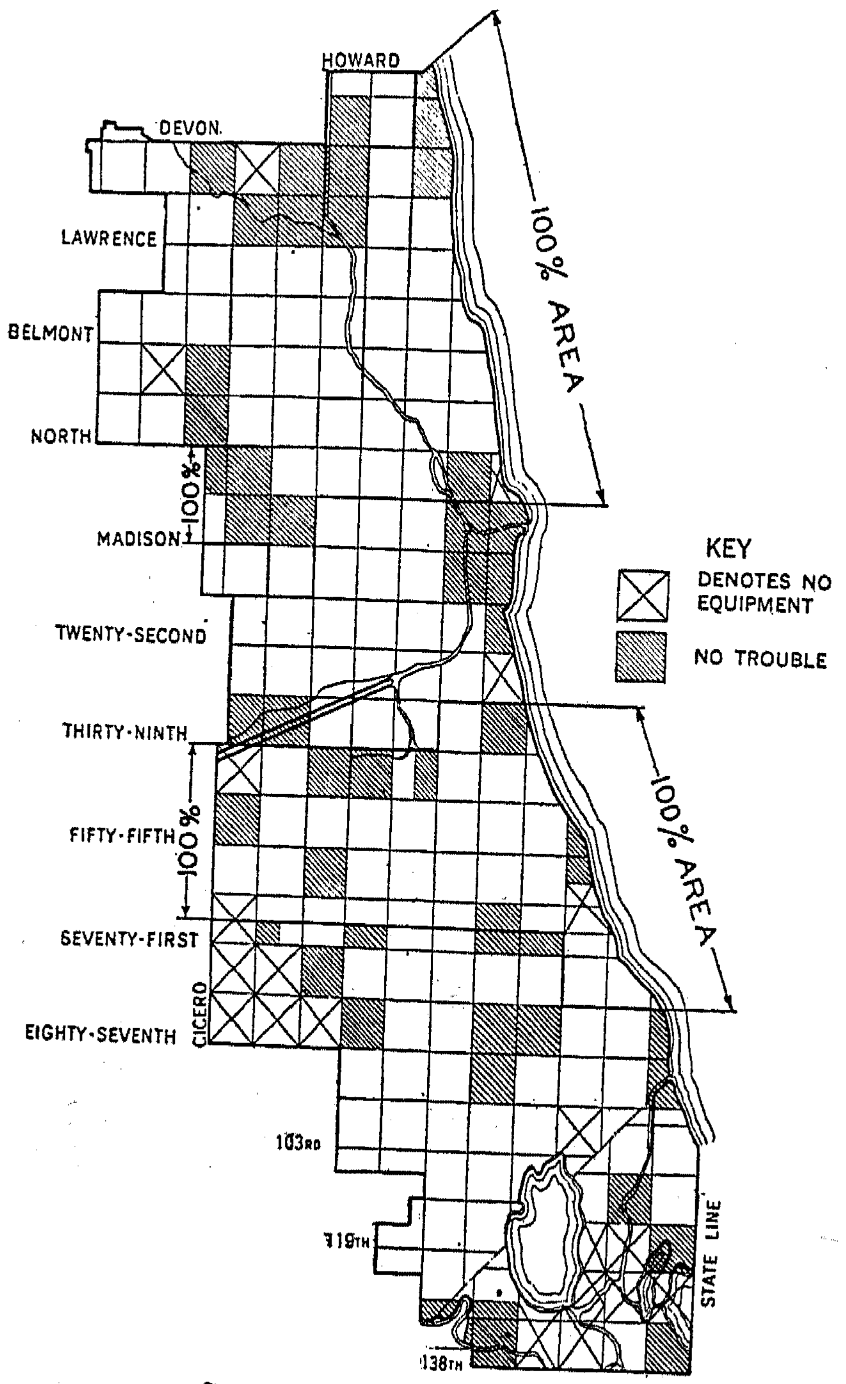


Fig. 18—Map Showing Sections (Square Miles) which Were Entirely Free from Lightning Troubles During 1915

should be protected by installing other arresters in the vicinity in addition to those on the transformer pole.

The figures in Table II for transformers above 15 kw. also show by the large percentage of these transformers the operation of the rules under heading XIII.

It is very evident from Figs. 11 and 12, as well as from several of the tables, that classes A and B protection are both considerably better than class C. Table VIII indicates that the per-

centage of fuses blown for class A is less than one-third of that of class C, while for the transformer burn-outs the ratio is about one to six.

XIX—Analysis of Class C Protection

As stated earlier in the paper, classes B and C protection cover all of the transformers outside of the 100 per cent areas or class A protection. If the transformers included in class B

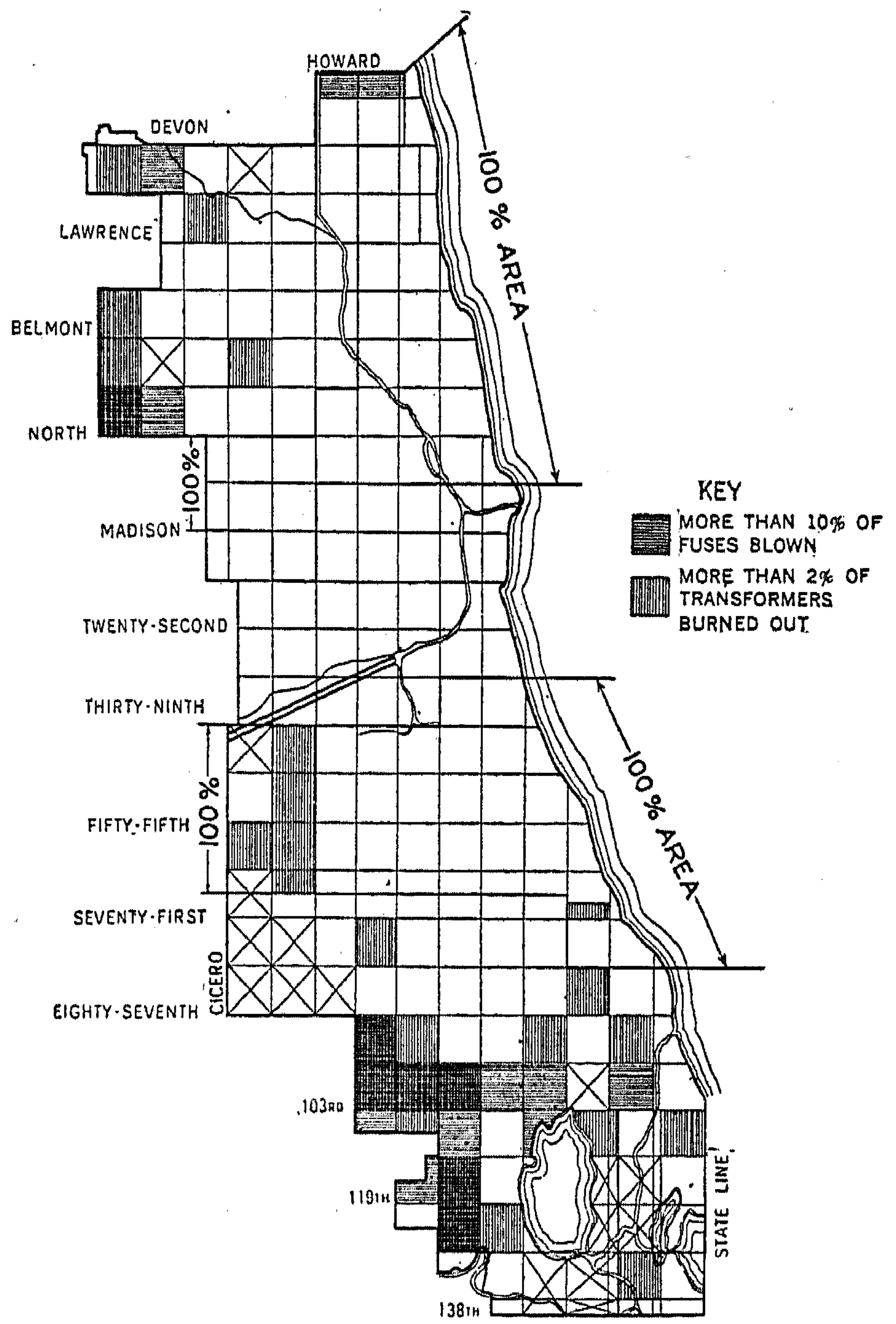


Fig. 19—Map Showing Sections (Square Miles) in which the Troubles from Lightning Were Several Times the Average

protection are for the moment ignored then the arresters installed for class B protection can be considered, relative to the class C transformers, as being installed on the line poles.

For the purpose of getting a general view of class C protection, Figs. 18 and 19 have been prepared. The former shows by the shading, with the section (*i.e.* square mile) as a unit, the areas in which there was no transformer trouble caused by lightning during the year 1915. Excluding the sections in which there are no transformers, it is found that within the 100 per cent areas

23 per cent of the total was entirely without trouble, while outside of the 100 per cent areas the corresponding figure was 26 per cent. These figures are so close that one can reasonably conclude that the entire absence of lightning trouble from extended contiguous areas indicates absence of lightning disturbances rather than perfection of the protection. This also means that the fact, that a comparatively few lightning arresters of any particular type have passed through an entire season without any trouble on the line or apparatus which they protected, is not to be considered as proof that the arresters are of value. It is probable that the absence of trouble may have been due to the absence of lightning disturbances at these particular locations.

Fig. 19 shows, by the shading, the areas in which transformer troubles due to lightning in 1915 were several times the average.

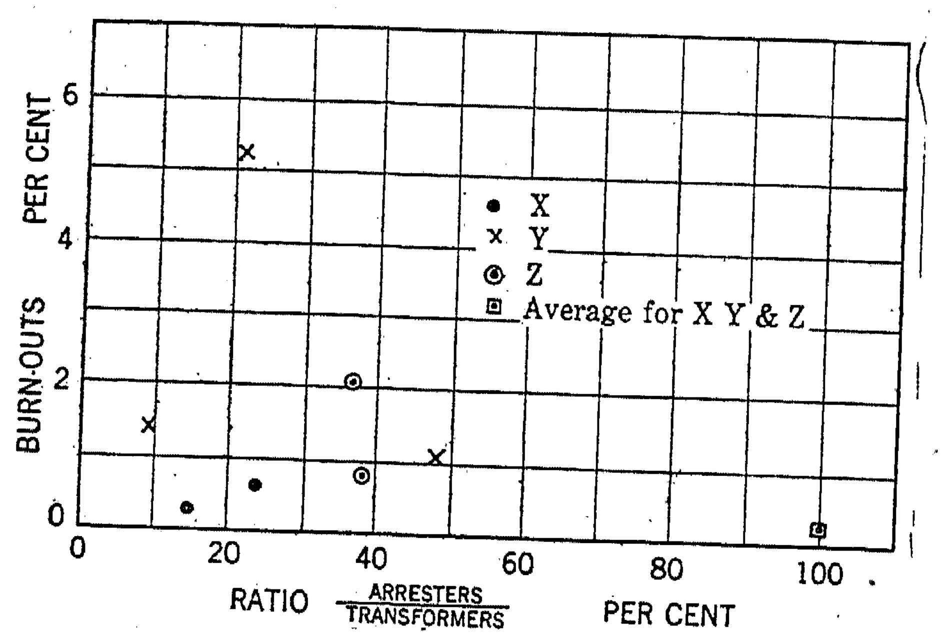


FIG. 20—DIAGRAM SHOWING FOR CLASS C PROTECTION THE RELATION BETWEEN THE RATIO OF ARRESTERS TO TRANSFORMERS AND THE TRANSFORMER BURN-OUTS

Comparing the percentage which these shaded areas bear to the total in the same manner as for Fig. 18, we find that the areas showing the fuses blown in Fig. 9 are 6 per cent and 28 per cent respectively for the class A areas and for the rest of the city. The similar figures for transformers burned out are 13 per cent and 33 per cent respectively. When considered with the results from Fig. 18, these figures appear to indicate that lightning arresters protect the transformers against a large fraction of the lightning strokes, and that the rest of the strokes, which are probably of a very high frequency and large volume, are beyond the capacity of the arrester.

By comparing the shaded areas on Fig. 19 with a map showing the number of transformers in each section, it can be noted that the shaded sections outside the 100 per cent areas are, in gen-

eral, the sections in which the number of transformers per square mile is small. An attempt has been made to plot a curve showing the variation of lightning trouble with the ratio of arresters to transformers, as shown in Figs. 20 and 21. The points in Fig. 21, showing the fuses blown, almost result in a curve. One point, however, is almost off the scale. This is the result of the storm of August 16th and if this particular storm is eliminated from the record because of its nature, before plotting results, then the storm of May 15th should also be omitted. The latter storm, however, affects other points so that the final result is not materially better than Fig. 21. In a general way, the conclusion can be drawn from this figure, that increasing the number of arresters reduces the percentage of fuses blown; that is, it improves the lightning protection. Taken in conjunction with

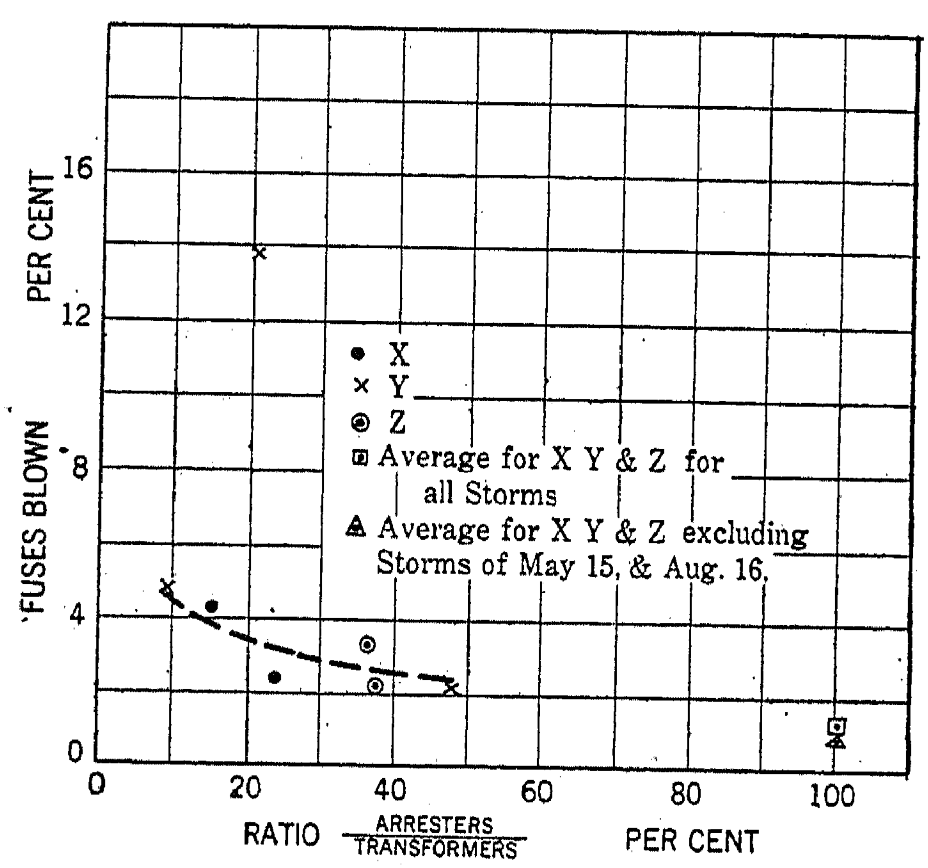


FIG. 21—DIAGRAM SHOWING FOR CLASS C PROTECTION THE RELATION BETWEEN THE RATIO OF ARRESTERS TO TRANSFORMERS AND THE PRIMARY FUSES BLOWN

the previous figure, the points on Fig. 21 appear to indicate that the installation of comparatively few arresters on a line will make an appreciable improvement in the lightning protection.

On Fig. 20 the points are so scattered that it is quite impossible to draw a line which would fairly represent average values. It is probable, however, that a part of this difficulty may be due to differences in the protective values of the several types of arresters.

Taking the several conclusions into consideration, it appears that, starting with the assumptions, (1) that lightning strokes

cover a wide range of frequency, and (2) that a lightning arrester acts like a pop-valve rather than like an umbrella, the behavior of the lightning arresters during a thunder storm, may perhaps, be described as follows. Some of the lightning strokes are of comparatively low frequency and moderate volume, so that an arrester placed anywhere along the portion of the line affected by the stroke will protect the transformers. This type of stroke is the only kind that is seriously affected by the old fashioned scheme of scattering a few arresters along the line poles.

For strokes of higher frequency, it becomes necessary to have the arresters nearer the transformers, and this may be accomplished in part by installing an arrester on the pole next adjacent to each transformer. This results in a considerable improvement by the elimination of strokes of moderately high frequency, and also of the lower frequency strokes that are of too great volume to be discharged by a single arrester. For strokes of very high frequency, the arrester on the pole next adjacent to the transformer is no longer sufficient, and the arresters must be placed immediately alongside the transformer. This eliminates a still further percentage of the lightning strokes from the list that cause damage. There still remain strokes of such high frequency and volume that a single arrester on the transformer poles becomes inadequate on account of its limited discharge capacity. This may account for the damage done to the transformers that are so protected.

Where the transformers are located at some considerable distance along a line, or at the end of a long line, the indications are that a single arrester on the transformer pole will again prove inadequate, and that in order to secure the best protection the rules should require, in addition, a certain maximum distance (not yet determined) between arresters, so as to protect against the lightning strokes of moderate frequency and considerable volume, which cannot be discharged by a single arrester and which are apparently a fair proportion of the total number of strokes.

One of the causes of the difficulty in attempting to secure average results from lightning conditions is well illustrated in Fig. 10. Upon making a critical examination of this map it will be noted that within the four sections adjacent to 111th and State Sts., there were five burned out transformers and 24 blown fuses, or a ratio of 1 to 4.8, while in the four square miles adjacent to 95th St. and Ashland Ave., there were 16 burn-outs and

TABLE XII.
SUMMARY OF RESULTS WITH CLASS C PROTECTION. ARRANGED BY AREAS.

Type of arrester	X			Y				Z		
Area No.	2	10	Total	4	11	20+ 21	Total	9+ 12	19	Total
No. of transformers	394	824	1218	1504	746	634	2884	1142	1054	2196
" arresters*	60	198	258	136	358	131	625	436	386	822
Ratio $\frac{\text{arresters}}{\text{transformers}}$ per cent	15.2	24.0	21.2	9.0	48.0	20.6	21.6	38.2	36.6	37.5
Burn-outs No.	1	5	6	21	8	33	62	8	22	30
" per cent	0.25	0.61	0.49	1.40	1.07	5.2	2.1	0.70	2.08	1.37
Fuses blown No.	16	19	35	72	16	88	176	25	35	60
" " per cent	4.1	2.3	2.9	4.8	2.15	13.9	6.1	2.2	3.32	2.74
Transformers below 5 kw. per cent	56	46	49	62	47	76	60	33	71	51

*Same as *B* transformers.

14 blown fuses, or a ratio of 1 to 0.9. At the former location it appears that there was a large number of strokes of lightning of moderate frequency and volume so that only 20 per cent of the total number of troubles resulted in burned out transformers. At the latter location there was apparently a group of very high-frequency discharges of considerable volume as indicated by the fact that over one-half of the transformer troubles resulted in burn-outs.

Similar evidence of erratic behavior of the lightning can be seen in the storm of May 15th, shown in Fig. 9. In this storm it will be noted that several transformers burned out near 55th St. and Crawford Ave., which were several miles distant from any other lightning trouble. The two burn-outs near 63rd St. and Crawford Ave., were on the same pole, one transformer, burning out in the early morning, was replaced by another during the day and was again burned out by lightning during the evening. In this case there was an arrester on the same pole. If one were inclined to draw conclusions from isolated cases, it might be concluded from this particular example that the presence of a lightning arrester on a transformer pole is a hazard.

On Fig. 9 there can also be noted, in the northern part of the city, a large number of fuses blown without any transformer burn-outs in the immediate vicinity. In particular, there is one group of such cases near Western & Lawrence Aves. It would, of course, be very interesting to learn whether this group of primary fuses were all blown by one stroke of lightning, or by a number of successive strokes. Such information is very difficult if not impossible to obtain.

XX—Conclusions

As a result of the experience in 1915, the rule under heading XIII was again altered last December, so as to require the installation of a lightning arrester with each transformer thereafter installed, regardless of its size or use. Later it was also decided to extend this rule to all transformers now installed having the class C protection. This is equivalent to stating that the 100 per cent areas are to be extended so as to cover the entire city. This work is now progressing as fast as the deliveries of lightning arresters will permit, and will probably be completed before the presentation of this paper. These changes in the rules were made on account of the improvement in service, which in the light of experience, might reasonably be expected. The net

result of the increase in the number of arresters will be an increase in the annual charges against the system of distribution, and as the saving in repairs to transformers is estimated to be not more than about two-thirds of the interest, depreciation, maintenance, etc., of the arresters, the additional expense must, therefore, be charged against improved service.*

An attempt has been made to set forth, during the discussion of the results, such conclusions as could be most readily drawn from the facts submitted. For convenience, however, these conclusions, together with others that appear to be warranted by experience, may be summarized as follows:

1. The transformer troubles during lightning storms may be reduced: (a) by the removal of the transformer primary terminal boards. (b) By the installation of lightning arresters.

2. Lightning arresters installed on the transformer poles are considerably more effective than if installed on the line poles.

3. When the lightning arresters are confined to the line poles, the protection against lightning is improved by increasing the number of arresters.

4. Whether the lightning arresters are on the line poles or on the transformer poles, the protection appears to be improved by an increase in the number of arresters per square mile or per mile of line.

5. Even in the most severe lightning storms, which apparently cover a given territory quite completely, there will be numerous extended areas within this territory which will be entirely free from lightning disturbances.

6. While a lightning arrester on the same pole with each transformer appears to be quite adequate protection in a region where the transformers are reasonably close together, the protection appears to be inadequate where the transformers are separated by distances ranging above (say) 2000 ft. (609.6 m.)

7. There is no serious difficulty in devising forms of safe construction for installing lightning arresters on the transformer poles. The construction is considerably simplified by the use of self-contained arresters which do not require inspection.

8. The modern types of arresters comply with the specification

*The calculations on which the above conclusion is based, are given in greater detail in a paper entitled, "Lightning Protection for Transformers on 4000-Volt Distributing Circuits," read before the National Electric Light Association at its convention in Chicago May 22nd to May 26th, 1916.

that a protective device should be less subject to trouble than the apparatus which it protects.

9. The modern types of lightning arresters are so free from trouble that the installation of a fuse in series with the arrester, for the purpose of disconnecting the arrester in case of trouble, is not warranted.

10. Absolute immunity from lightning troubles cannot be secured by an installation of lightning arresters.

11. For the conditions in Chicago the installation of lightning arresters for the protection of transformers is not warranted by the saving in the cost of repairs to transformers, and can be justified only as a means for improving the quality of the service.

12. Great care should be used in attempting to draw general conclusions from the experience obtained from a few arresters, or during a single season or from a limited area.

13. The use of the several schemes for the improvement of the lightning protection that are herein described can reasonably be expected to remove at least 90 per cent of the lightning troubles formerly experienced.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 28, 1916.

EXPERIENCE AND RECENT DEVELOPMENTS IN CENTRAL STATION PROTECTIVE FEATURES

BY N. L. POLLARD AND J. T. LAWSON

ABSTRACT OF PAPER

The protective features described in this paper are some of those now in use on the system of the Public Service Electric Co. which serves a population of about 2,200,000.

The most interesting protective devices and schemes discussed in this paper are as follows:

Aluminum cell arresters; arcing ground suppressor; faulty cable localizer; cable testing; high-potential and high-frequency testing; generator bus connection scheme; exciter connection scheme; reactors; relays; multi-recorder; insulation resistance recorder; air washers; resistance bulbs and thermo-couples; dampers on air-blast transformers; coherer alarm devices; potential indicating devices.

THE ENTIRE territory served by The Public Service Electric Co. comprises three principal divisions; the Northern, Central and Southern, which include the more densely populated sections of the State of New Jersey. Fig. 1 shows a diagram of the transmission system.

The Northern Division consists of eight generating stations having a combined capacity of 148,000 kw. and feeding 33 substations.

The Central Division consists of five generating stations having a combined capacity of 17,800 kw. and feeding 13 substations.

The Southern Division consists of four generating stations having a combined capacity of 32,000 kw. and feeding 17 substations.

In the larger stations, current is generated at 13,200 volts, 3 phase, both 25 and 60 cycles, and in most cases is distributed at that voltage between the various stations and substations, through 260 miles (418.4 km.) of underground cable and 425 miles (683.9 km.) of overhead lines.

In the smaller stations, current is generated at 2400 volts, two-phase, 60 cycles, and distributed locally at that voltage. That part of the current not consumed locally, is stepped up to

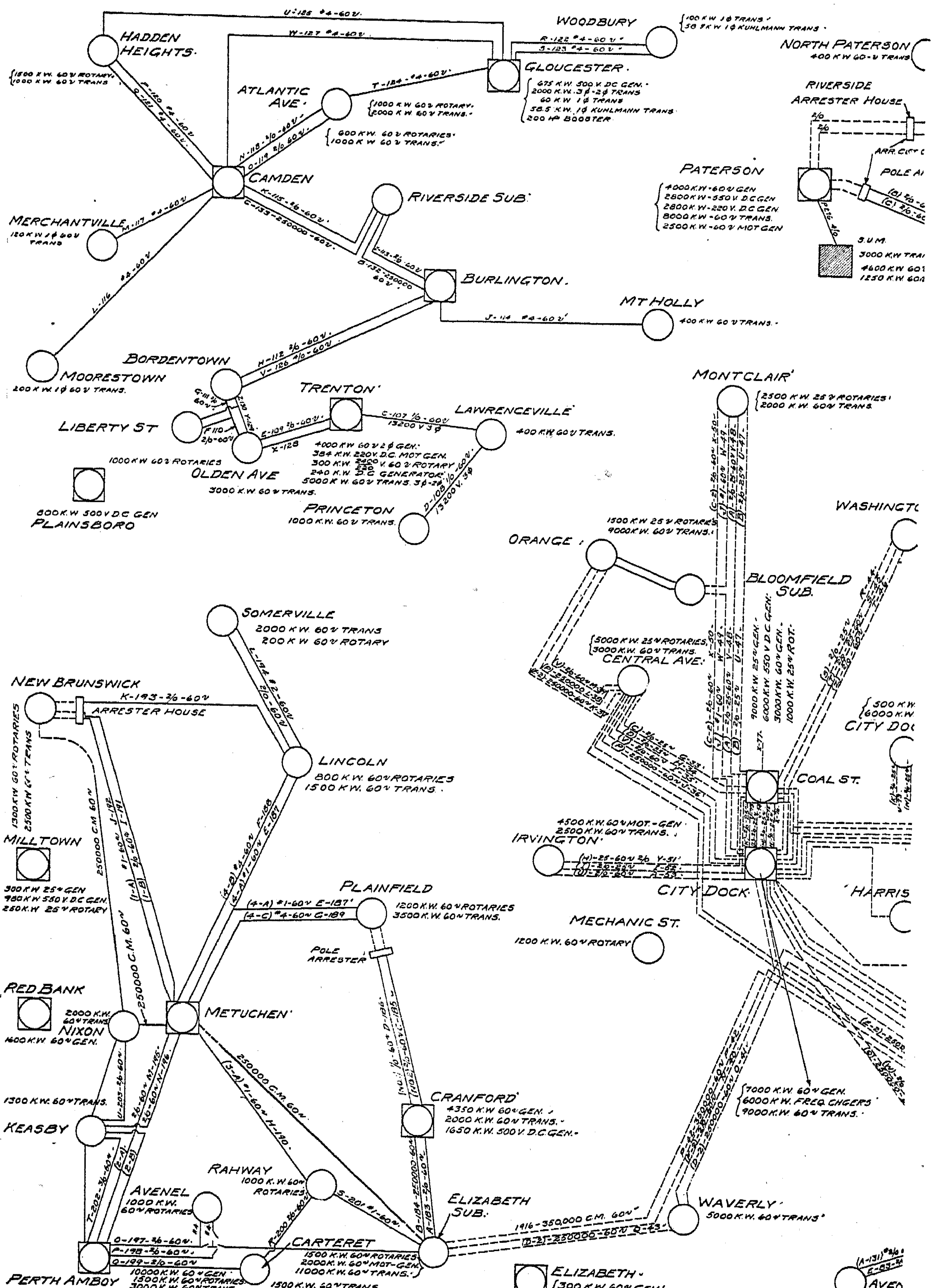
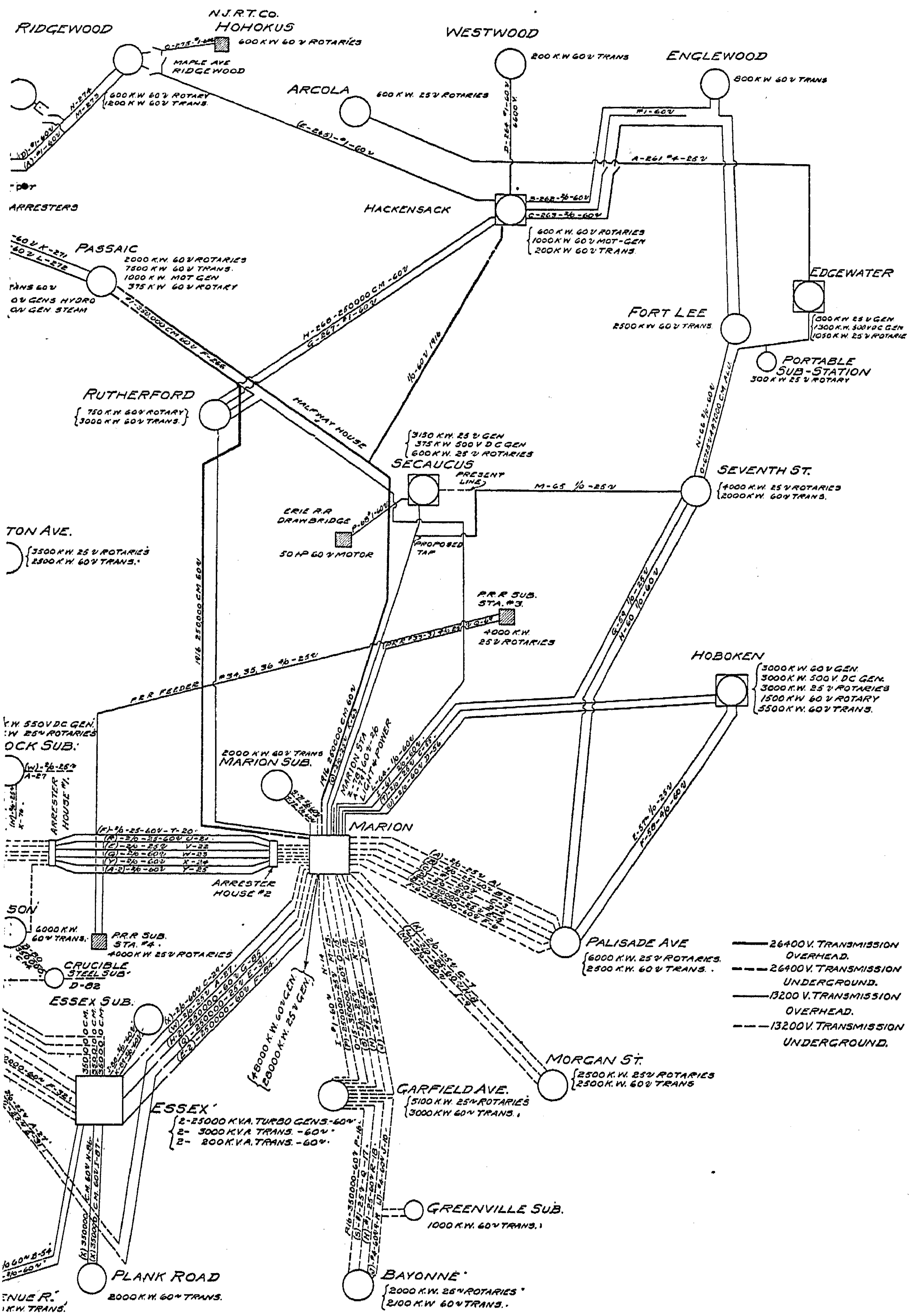


FIG. 1—GENERAL TRANSMISSION SYSTEM



OF THE PUBLIC SERVICE ELECTRIC COMPANY

13,200 volts, three-phase, by means of Scott-connected transformers.

In certain sections our loads have increased so rapidly that it has been found impracticable to take care of any additional load and maintain the proper service at these points. In order to take care of these sections it was found necessary to change some of our transmission lines to 26,400-volts, and to install step-up and step-down transformers with a ratio of two to one.

The method of operation is to run all stations in multiple, which necessarily means that the largest and most economical stations deliver the most output. The older and smaller stations are used at off-peak and as stand-by stations.

Six years ago, in the Northern Division, there were too many cable failures in relation to the mileage. The following table shows the number of shut-downs in the Marion zone since 1913, and a classification of these shut-downs for 1913, 1914, and 1915. A few of the cables are operated either as spare cables, 25 or 60 cyles, and these are included in the total mileage of both the 25 and 60-cycle cables. The total number of line and cable interruptions since 1913 has decreased while the mileage has increased. This was brought about by eliminating as rapidly as possible all equipment that was proved defective and by the use of such safety devices and connection schemes as are described later.

CLASSIFICATION OF TROUBLES RESULTING IN INTERRUPTIONS TO SERVICE

Classification	1913				1914				1915			
	25 ~		60 ~		25 ~		60 ~		25 ~		60 ~	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Insulator failures	12	22	30	20	15	19	14	13	3	6	6	5
Cable failures	2	4	21	14	4	5	12	10	14	26	18	15
Storms	9	17	16	11	11	14	15	13	8	15	22	19
Outside interference	9	17	22	15	7	9	27	24	5	10	19	16
Central station app.	3	5	4	3	1	1	5	4	5	10	3	3
Substation app.	2	4	7	5	20	26	11	10	12	23	10	8
Secondary feeders	5	9	23	15	8	10	16	14	..	..	6	5
Operating mistakes	2	4	10	7	2	3	4	4	..	..	5	4
No apparent cause	10	18	15	10	10	13	9	8	5	10	25	22
Total failures	54		148		78		113		52		114	
" " per mile		.39		.69		.56		.44		.38		.40
Miles cable	83		90		83		121		83		141	
Miles overhead	54		123		54		133		54		144	
Total miles	137		213		137		254		137		285	

Aluminum Cell Arresters

While the installation of aluminum arresters has made the apparatus trouble disappear almost completely, and as the table shows, the failures of cables have decreased, it has, as might be expected, not given all the desired protection to the cables. The reason for this is probably that the surges on the cables are in the form of distributed charges and the potentials rise locally in the cables entirely beyond the protective influence of the arrester.

Upon analyzing these cable failures, it was noticed that the majority of them were caused by faults to ground which later developed into short circuits. At this time, due consideration was given to the question of grounding the neutral of the system, but after taking all the factors of the problem into account, such as continuity of service etc., the idea of grounding the neutral was abandoned and it was decided that, as far as the system was concerned, the best remedy was the arcing ground suppressor.

Arcing Ground Suppressor

An arcing ground suppressor was installed in our largest generating station and numerous aluminum cell arresters on different parts of the system, believing that they would be the remedy best adapted to meet our requirements.

The arcing ground suppressor has now been in service about five years and the records show that it has operated in every case where a fault to ground occurred, by extinguishing the arc, and preventing an interruption to service.

The arcing ground suppressor consists of three single-pole independent motor-operated oil switches, electrically and mechanically interlocked, to prevent more than one operating at the same time. Each switch is connected to ground on one side and to the bus on the other. The suppressor is controlled by a balanced three-phase potential relay, which remains inactive while the system is balanced, but when unbalanced, due to a ground on one phase, it operates the corresponding phase of the suppressor, which, in turn, grounds the same phase of the bus; thus shunting the current and extinguishing the arc. In cases of short circuit, an extra precaution is taken to prevent possible operation of the suppressor by the addition of an overload relay which opens the control circuit of the suppressor.

A more detailed account of the arcing ground suppressor,

its action and effect on a transmission system, can be found in a paper written by E. E. F. Creighton and J. T. Whittlesey published in the TRANSACTIONS of the A. I. E. E., Vol. XXXI, 1912, p. 1881.

FAULTY CABLE LOCALIZER

Working in conjunction with the suppressor is a device known as the faulty cable localizer, which serves the purpose of indicating the particular feeder on which an arc to ground occurs.

This device consists of a relay connected in series with the neutral of the feeder current transformers. When a ground occurs, the secondary current of the transformers becomes unbalanced, and causes the relay to operate. This in turn, rings a bell and lights a pilot lamp which indicates the faulty feeder. It takes about 0.15 of a second for the localizer and 0.3 of a second for the suppressor to operate.

There is one record of a 15-minute interruption to the service in the Northern Division caused by a cable end bell short-circuiting on an armature lead of a generator in one of our stations, before the suppressor and localizer were installed. Shortly after the suppressor and localizer were put in service, the same thing occurred again and the situation was handled in such a manner that no one outside of the power station was the wiser. A number of instances are on record where a ground has occurred on substation buses without an interruption to service.

CABLE TESTING

As a further means of reducing our cable troubles to a minimum we made a careful investigation of the possible causes of failure.

For the first few years, all cable was installed by the manufacturer but we finally took over this work ourselves, with the idea of improving the factors entering into cable installation as much as possible.

A thorough study was made as to the best method of making cable joints and particular attention was given to such factors as

1. Favorable weather conditions,
2. Elimination of impurities, air and moisture.
3. Application of insulating varnish between each layer of tape.
4. Careful and even winding of tape.
5. Improving the human element.

Aside from installation precautions, we have made it a practise

to inspect cable during the process of manufacture, and to see that our cable specifications are strictly adhered to.

All cables are tested with 26,000-volts for three minutes before putting them in service, but we do not make a practise of testing them periodically. In case there are indications of trouble on a cable while in operation, it is cut out of service, given a test of 26,000 volts for three minutes, and returned to service in case no failure occurs.

In our opinion, a 13,200-volt cable should not be tested at a voltage higher than 26,000, since our experience has shown that too high a testing voltage often weakens the insulation at some point, which weakness finally manifests itself in a complete breakdown, even under normal operating voltage.

High-Potential and High-Frequency Tests

Our line insulators used a number of years ago consisted of many different types, no one type having been standardized. The old insulators not only spilled over during trouble but also became punctured frequently. The insulator creepage surface was then increased and the insulators tested with high-potential 60-cycle current, but without satisfactory results.

About two years ago, we started testing with high-frequency and were soon convinced from the results obtained that the insulators were not capable of standing this test. Various types of insulators were then experimented upon and a design finally adopted having a ratio of puncture to flash-over of about 2 to 1. Now, every insulator before being placed in stock or used on the lines is given a 15-second high-frequency test. Although these insulators are previously tested at 60-cycles, about 2 per cent fail to pass the high-frequency test.

Generator Bus Connection Scheme

Station capacities have increased so rapidly in the last few years that the bus arrangement has become a matter of vital importance in the protection of both apparatus and service. The ideal arrangement is one that secures the greatest amount of protection to the apparatus, and at the same time localizes and minimizes the effect of trouble.

Two years ago, before beginning work on the new Essex power station, a thorough study was made of various bus schemes and after analyzing those used by the large power plants of this country, it was decided that none of them would be satisfactory.

A bus arrangement was then designed which, in our estimation, would approach the nearest to the ideal, and called the "selective" bus scheme, which is shown in Fig. 2.

The considerations that governed in deciding on this bus layout are as follows:

Flexibility
Simplicity
Limitation of abnormally high currents.
Continuity of service.

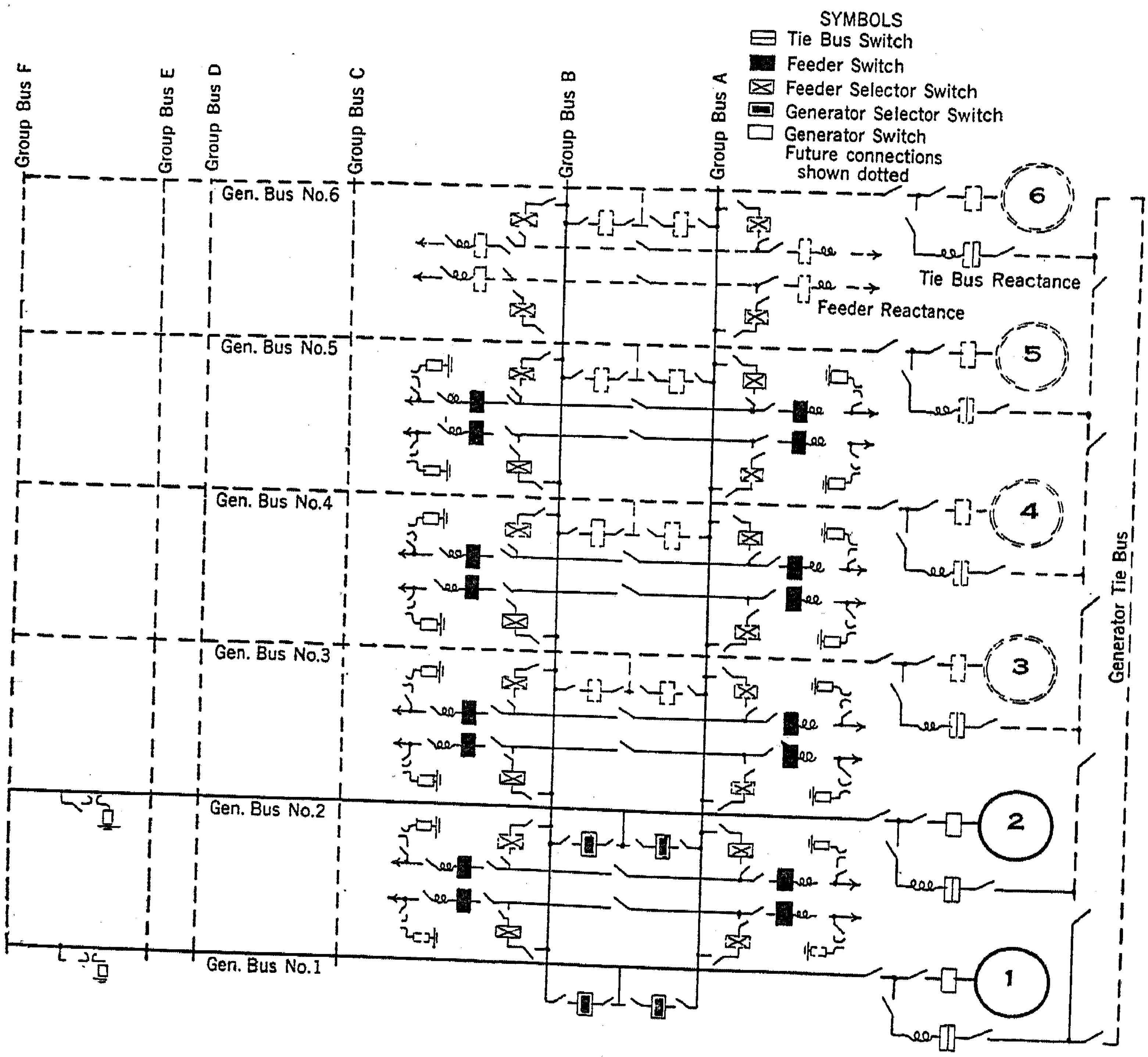


FIG. 2—SELECTIVE BUS SCHEME

The scheme is made for six generators and consists of one loop tie bus, six generator buses, and six feeder group buses of ten feeders each.

This arrangement of connections is a new application of the old arc board scheme and is the most flexible layout known. By means of the feeder-selector oil switches, the feeder oil switches can be connected to one or the other of two given

group buses; for instance, the twenty feeders on group buses *A* and *B* can all be connected to group bus *A* or group bus *B* or part to each group by twos.

The maximum flexibility in operation is obtained due to the fact that each generator may be connected directly to any part or parts of the load desired.

The generators are connected to a loop tie bus through tie bus reactances and can be operated in parallel at all times, if desired.

Exciter Connection Scheme

The exciter connections are fully as important as the main a-c. bus connections, inasmuch as the maintenance of the a-c. generator voltage depends upon the reliability of the excitation. In order to secure a dependable excitation service, several sources of supply should be available. The bus should be so arranged that a failure of one source cannot affect the others, except through its effect momentarily on the main bus voltage. The ultimate exciter system that will be adopted in the Essex station is clearly shown in Fig. 3.

Each generator has a direct-connected exciter, three spare exciters and a battery being available for emergency use. Each source of excitation has its individual bus. In case of voltage failure of one of the direct-connected exciters, a low-voltage relay instantly closes the battery breaker, thus connecting the battery to the affected exciter circuit. Immediately after, the breaker of the exciter in trouble opens, due to reverse current. An emergency exciter may then be started up and paralleled with the battery and the battery disconnected and left ready for emergency service again.

A contact-making voltmeter is provided for maintaining the exciter battery voltage automatically at operating value at every instant.

Reactors

Bus Tie Reactors. At the present time, generators of such large capacity are being used that it is necessary to protect them from the effects of disastrous short circuits by means of internal or external reactance. Where several generators are operated in parallel, it is essential that bus-tie or bus-section reactors be used in order to prevent the combined capacity of all the generators from feeding into any one point of short circuit. Bus-section reactors will limit the current on any one section but take up valuable space in the bus, complicate the connections, and in

cases where parallel feeders are connected to different sections of the bus, it is difficult to obtain balanced currents in these feeders.

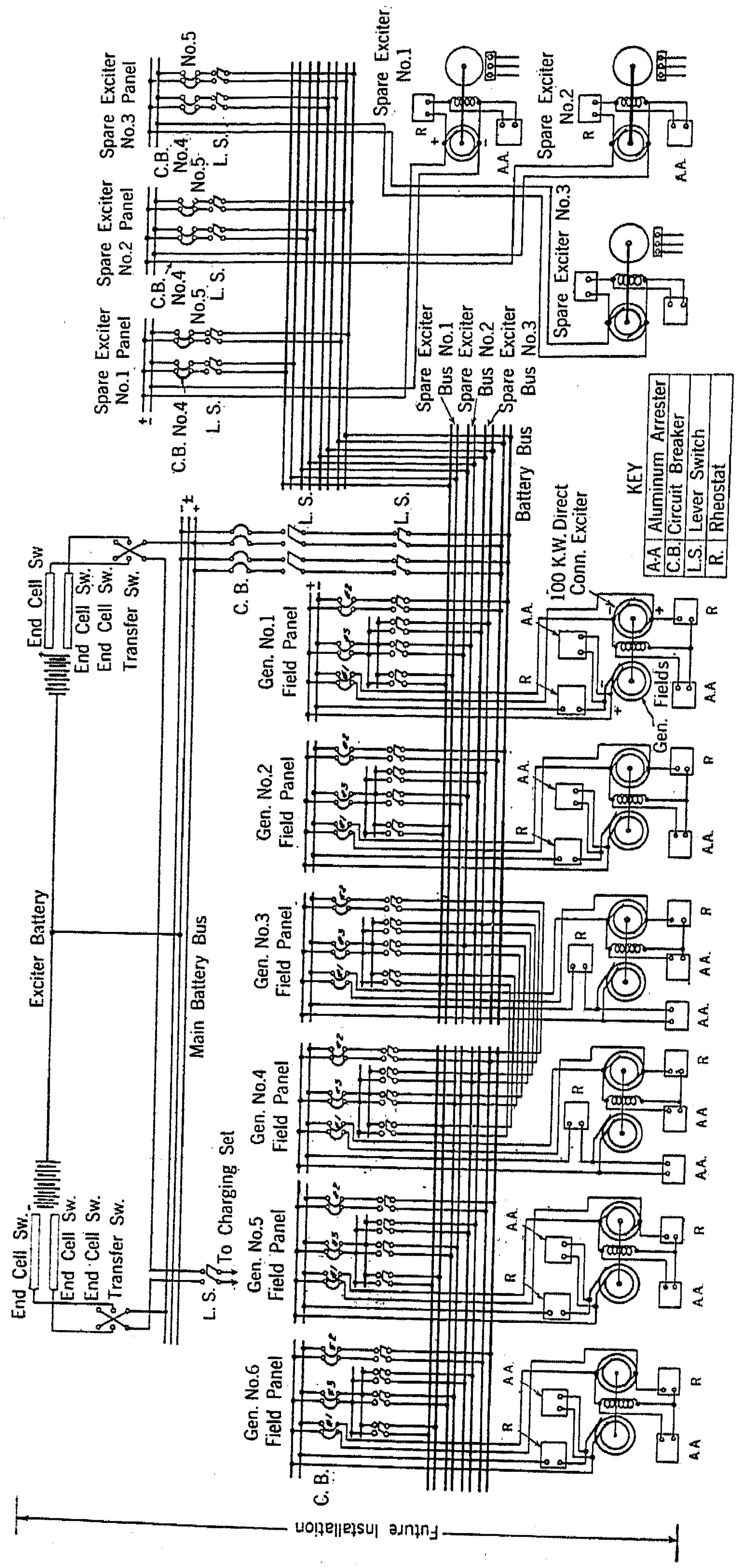


FIG. 3—EXCITER SYSTEM, ESSEX POWER STATION

In the selection of reactance coils best adapted to meet our requirements, we were governed by the following factors:

Cost

Low losses

Space occupied

Temperature rise
Ability to stand short circuits
Freedom from inflammable material.

The use of tie-bus reactors has none of the disadvantages of the bus-section reactors, and does limit the amount of

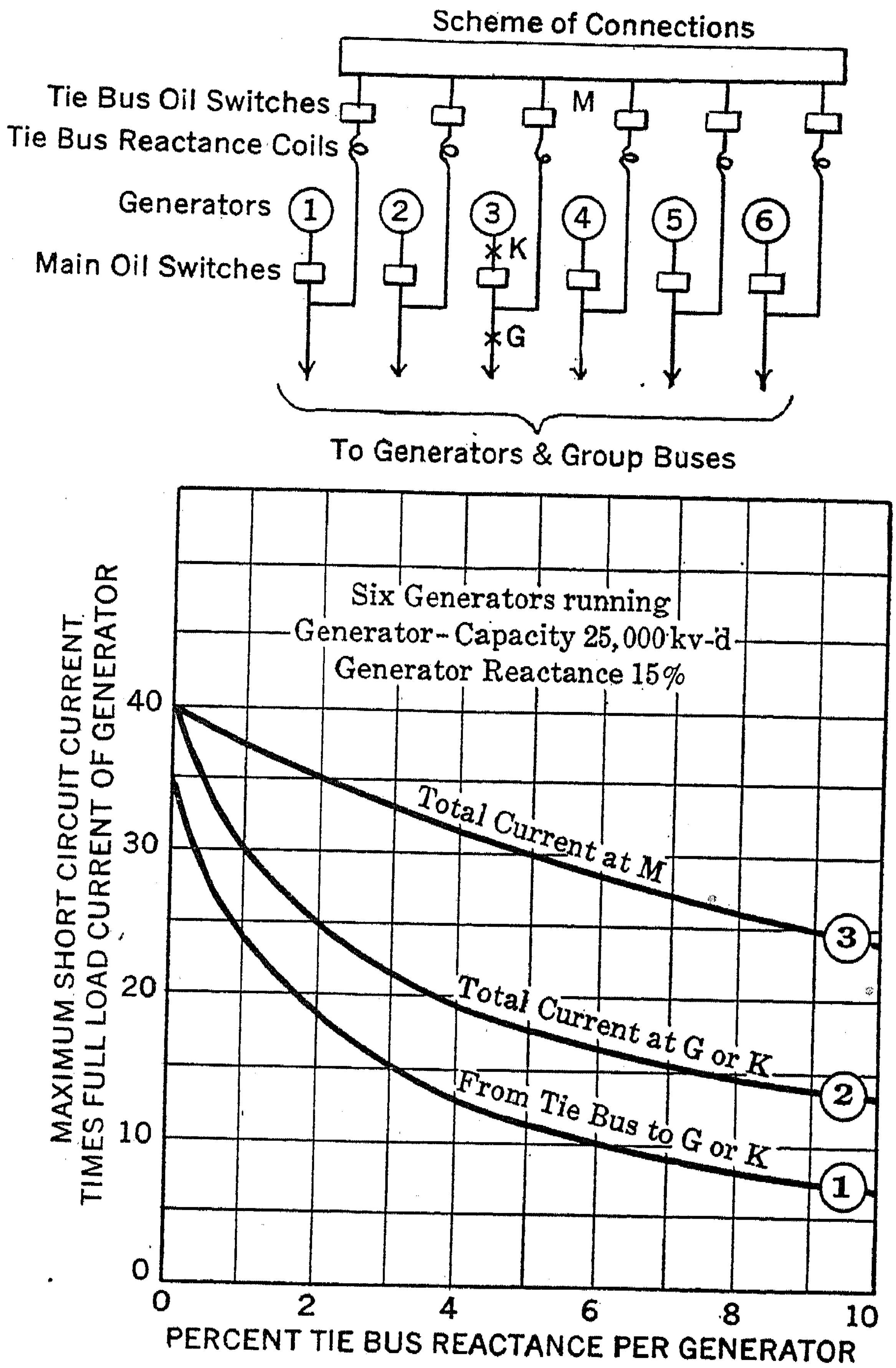


FIG. 4—EFFECT OF TIE BUS REACTANCE SHORT CIRCUIT CURRENT

short-circuit current on any one section to any value desired, depending upon the amount of reactance used. For this reason, tie-bus reactors will be used, connected as shown in Fig. 4.

The curves in this figure show the effect of tie-bus reactance on short-circuit currents; assuming that short circuits occur at the points G, K and M. The per cent tie-bus reactance per

generator is plotted against the maximum short-circuit current times full-load current of generators. Assuming that a short circuit occurs at points marked G or K on generator bus No. 3, the maximum short-circuit current flowing into either of these points from the other five generators is shown by curve No. 1. Curve No. 2 shows the total short-circuit current of all six generators. Curve No. 3 shows the maximum short-circuit current of six generators feeding into a point marked M on the tie bus. The worst condition, as far as the oil switches are concerned, is to have a short-circuit at either one of the points G or K. The main generator and tie-bus oil switch must open the short-circuit current of five generators when the trouble is at K; when at G the main generator oil switch is only required to open the short-circuit current of one generator. The slope of the curves is greater for the first few per cent of reactance, and gradually becomes less as the per cent of reactance is increased; a value greater than 10 per cent being impracticable. It therefore follows that a percentage of reactance should be selected which will limit the short-circuit current to a safe value and still not cause the coils to be excessive in size or cost.

Feeder Reactors. Two years ago the generator capacity in our Marion Station had increased to such an extent that the oil switches, in some instances, were unable to rupture the excessive short-circuit current. This unsatisfactory condition compelled us to install reactance coils on all the 60-cycle feeders. Aside from the short-circuit limiting feature of the reactance coils, we believed that a better selective action of relays would result, if reactance coils were installed on both ends of the tie feeders connecting the Marion and City Dock stations. After studying the conditions then existing, reactors were also installed on the City Dock end of the 60-cycle tie feeders.

Five per cent reactance was chosen as the amount best suited for the radial feeders and two and one-half per cent at each end of the tie feeders. (As a matter of fact, we installed five per cent reactance coils and used the two and one-half per cent taps.) There were at this time, seven tie feeders between Marion and City Dock and five or six of these operated in parallel at all times. Each feeder consisted of 2.5 miles (4 km.) of cable at the City Dock end, three miles (4.8 km.) of aerial line and one-half mile (0.8 km.) of cable at the Marion end.

If a fault occurred on one feeder there would be 2.5 per cent reactance between either station bus and the fault and an addi-

tional 5 per cent reactance between the unaffected tie feeders and the faulty one. As anticipated, this arrangement gave the very best selective action of our relays in case of trouble.

About one year after the installation of the reactance coils, the tabulated records of failures on tie feeders showed that instead of being faults to ground as formerly, they were in most cases, short circuits. Shortly after this, five sets of aluminum cell arresters were installed 2.5 miles (4 km.) from the City Dock station at the point where the underground cables connected to the aerial lines, with a hope of relieving the local potentials in the cables, but satisfactory results have not been obtained up to the present time.

By a comparison with the 25-cycle system, where no reactors are used on the feeders, it seems evident that the change in the nature of the faults on the 60-cycle system might surely be attributed to some unknown result of the combination of the inductance of the reactor and the distributed capacitance of the cable. To overcome rises of potential at the terminals of the concentrated inductance in the reactors, aluminum arresters were installed on the buses, which, with the arresters already installed on the feeders, placed protection on each side of the reactance. Even with this protection, all the sources of trouble have not been reached, as indicated by the continued failures of cables, and two cases of internal failure of reactors which might properly be attributed to a local rise of voltage internally in the reactor.

It is evident that these troubles are of a deeper nature than would appear on the surface and we are laying plans to make a further study of the surges both from the standpoint of localization of potential and natural frequency.

It seems proper to attribute these troubles to surges. If the troubles were due to weak insulation, they should occur as frequently on the 25-cycle system as on the 60-cycle system, which, as already recorded, is not the case.

Relays

During the early days of the electrical industry more attention was given to the protection of apparatus than to maintenance of service and therefore, the aim of the operating man was to remove the short circuit as quickly as possible.

In short, the old idea of protection was one of adjusting relays and circuit breakers to protect apparatus against overloads.

Later, with the improvement of station apparatus and its ability to withstand short circuits, the thought gradually took root that the function of the relay should be primarily to protect against interruption of service to the customer. The result is that the modern idea with reference to relays, is to insure continuity of service. It is only in recent years that this idea has developed and central-station men today do not fear breakdowns in apparatus as much as service interruptions.

Carrying out the idea of service protection, operating companies of late years have gone to considerable expense in electrical features related to the transmission system. The best insurance against interruptions has demanded the use of duplicate feeders over more than one route, such as by means of tie lines, parallel feeders, ring connected feeders, etc. This means a larger and more complicated system, an increase in liability of breakdowns, and therefore a more serious problem as far as relay protection is concerned.

It is obvious, that practically all interruptions in a transmission system will be minimized if faults are easily and quickly removed before they have had time to cause serious trouble.

In order to determine the proper setting of instantaneous overload, inverse-time-limit and inverse-definite-time-limit relays which are more commonly used on a system of distribution, it is necessary to know the characteristics of the system as well as the characteristics of the generators, automatic apparatus, circuit breakers, regulators, etc., before anything can be done along these lines, and before the time elements of relays can be adjusted, the following information is necessary:

1. The instantaneous short-circuit value of current through each conductor to which the relays may be applied.

2. The sustained short-circuit value of current through each conductor.

3. The time in changing from 1 to 2.

4. The time required for various automatic circuit breakers to open the circuit after application of current through the trip coils.

5. The safe current-opening characteristics of various circuit breakers.

6. The time characteristics of the various relays.

7. The probability and amount of flow of energy in the case of circuits operating in parallel.

If these seven items were known with any degree of accuracy,

it would enable one to accurately set relays, but as a matter of fact, it is almost a physical impossibility to arrive at these seven conclusions with any degree of certainty. For instance, the values of short circuits depend particularly upon the characteristics of the generators and also upon the impedance of the circuit to the point to which the relays are connected. The further the point of the short circuit from the generator, the less will be the difference between instantaneous and sustained short circuits, or between item 1 and item 2, providing the same apparatus is included between the short-circuit point in question and the generator.

Again, operating companies whose growth extends over a period of years, must necessarily operate generators of different internal characteristics. For this reason, the results obtained from setting a relay for values 1 and 2 for a machine purchased several years ago, will not be the same for a generator installed recently.

Assuming for the moment that the seven items listed are known and an attempt is made to accurately time relays for selective action, the accuracy of current values required to trip a relay can be left as a matter of small concern, for when a short circuit occurs, the current setting of relays is usually exceeded by at least several hundred per cent. This applies equally well to inverse-time or definite-time relays. It is an impossibility to get selective setting with the inverse-time-limit relay because it has the unfortunate characteristic of being instantaneous with a heavy overload. This characteristic prevents the use of this type of relay for selective action because a short circuit of sufficient magnitude will cause all the relays from the fault to the source of supply to become instantaneous, and thus any or all of the relays are liable to trip out instead of only the ones nearest the fault.

Better results can be obtained by the use of an inverse-definite-time-limit relay, the time setting of which depends upon the damping action of a permanent magnet on an aluminum disk, giving as great a degree of accuracy as can be obtained in the calibration of watt-hour meters used in connection with a torque compensator.

This type of relay is more accurate and allows closer setting than any other type, and when once set, remains the same, but in an extensive system, the results obtained from its use are nevertheless disappointing. The reason for this is simple, when

it is considered that the time interval between successive circuit breakers should be equal to the time taken for the circuit breaker to open its arc, plus a margin of safety to include variation, and if there are several feeder sections in series and the trouble should be near the generating end, the short circuit may not be cleared for several seconds, which means, of course, a loss of all synchronous load on the system, or in other words, a complete interruption to the service.

From the foregoing, it can be seen that irrespective of the character of the distribution system, it is practically impossible to isolate faulty cables or lines by the relays most commonly used, and therefore the records of most operating companies show that faulty feeders usually interrupt a large area and a great many more consumers than is necessary.

With the relays more commonly used, the most satisfactory results are obtained by using them with a radial distribution system; or, in other words, most operating companies get the best results by adapting their systems to meet the faults in the relay rather than design a relay for a minimum cable outlay.

A well designed transmission system is one which has the following characteristics.

1. Safety in operation for employees and the general public;
2. Suitability of supply for the purpose required;
3. Freedom from interruption.

Therefore, the question resolves itself into one of design, as has been shown.

Failure of supply is usually caused by breakdown of transmission and the primary precaution is therefore careful attention to design, manufacture and maintenance of the various parts of the system, but since no apparatus can be made absolutely immune from breakdown or external damage, the secondary precaution is to make arrangements so that the effects of a breakdown to any part of the system are localized as much as possible.

In some cases, such precautions may mean increased capital cost, but undoubtedly result in a net economy if a broad view is taken.

Fortunately, however, well designed apparatus does not necestarily cost more than badly designed apparatus and it is possible to cheapen the system by closer localization of breakdowns.

Balanced Selective Relay. In connection with the seven tie feeders between City Dock and Marion, mentioned elsewhere in

this paper, so much trouble was experienced due to the lack of a selective action of the relays, that a new type of relay known as the "balanced selective relay" was finally installed at each end of these feeders.

The relay coils are connected in series with current transformers of the tie lines. This causes the current in each coil to be proportional to the current in the cable to which it is connected.

Only a single phase of each cable is taken care of by a single relay and there are as many coils on the relay as there are cables. For instance, with seven cables on a three-phase system there are three relays with seven coils per relay.

Each coil on each relay is mechanically balanced against each other coil. The effect of this is that any strong coil can overcome any weak coil. In case a short circuit occurs on one cable, the current in the faulty cable will of course be greater than the current in any other cable.

Therefore, the coil connected to the current transformer on the faulty cable will have the strongest pull and will close the tripping circuit of this oil switch.

However, if none of the parallel cables are short-circuited, but trouble occurs on some radial cable, the relay will remain balanced and none of the good cables will be erroneously tripped out. The relays operate simultaneously at both ends of a faulty cable and their operation is not affected by fluctuations in voltage due to trouble or change of phase angle between voltage and current. With this particular type of relay, it is necessary to have not less than three feeders in service, in order to secure perfect operation under all conditions. It should be further borne in mind that reactance coils are installed on both ends of the tie feeders in order to secure the best selective action of the relays. It is questionable whether the relays would operate as satisfactorily in all cases without the aid of these coils. The successful operation of these relays is limited to three or more feeders, therefore, they cannot be used on other parts of our system where there are but two parallel cables between stations.

Since the installation of the balanced selective relays, we have had no case of cable failure on the tie feeders where the relays have not operated properly and there have been more than fifty cases of trouble.

Our operating conditions are such that at times there are but two tie feeders in service, therefore on these occasions it is neces-

sary to disconnect the balanced selective relays and depend on overload protection.

Judging from past experience with different types of relays, a pilot wire relay would seem to be the best one to adopt if it were not for the trouble and expense entailed by the necessity of the pilot wires. Therefore, some scheme based on the pilot wire principle, having all the advantages and none of its disadvantages would be an ideal one for our interconnected system.

Our investigation shows that the nearest substitute for the pilot-wire scheme and one that has practically all the advantages is the split-conductor principle. During the coming year we expect to make several installations of this character.

Multi-Recorder

The multi-recorder is a device for recording the time to the fraction of a second of the sequence of action of oil switches, circuit breakers, potential indicating devices and aluminum cell arresters. A record of this kind is invaluable to the station man in analyzing troubles or ordinary switching changes.

In order to have complete information on the performance of station apparatus under all conditions, it is highly desirable to have records of the closing and opening of circuit breakers, operation of lightning arresters, appearance and duration of high voltage in the lines and the occurrence of grounds and short circuits.

At the time of writing this paper the installation of the multi-recorder is not complete, therefore we are unable to give any actual operating experience with this instrument.

Insulation Resistance Recorder

The insulation resistance recorder is an instrument which gives a daily graphic record of the insulation resistance of the system. The results obtained so far from the use of this instrument have been rather disappointing, due to the fact that there are so many old insulators of different insulation characteristics. When the insulators are all changed so that they will have the same characteristics throughout the system, we can, by establishing a point on the chart which might be called "dangerous," but which is well above the breakdown point, give the operator an opportunity to report when the insulation of the system reaches this value. By isolating the transmission circuits one at a time, the line in question can be removed from the system and later

by high-potential testing or other methods, the bad insulators can be located and removed from the line.

In using this instrument on lines where the insulators have been standardized, very good results have been obtained. Its use has also shown the need of increasing the insulating qualities of porcelain, which is something that we did not know before.

Air Washer

The capacity of a generator is directly dependent upon its temperature. In order to keep its temperature as low as possible, it must be supplied with a sufficient amount of clean, cool humidified air.

The specific heat of air being low, it is necessary that it be humidified in order to increase its heat carrying qualities sufficiently. It is also necessary that the air be free from impurities in order to prevent a partial or complete closing of the machine ventilating ducts.

A well designed air washer will satisfy all the requirements mentioned above.

Air washers are used in connection with our largest turbo-generators and our experience leads us to believe that their use is almost a necessity; particularly where the conditions are such that the air contains a great many impurities. If an air washer is not used, it is necessary to remove the rotor of a machine periodically and clean the ventilating ducts or in time they will become so clogged with refuse that over heating will result and a burn-out occur.

Where large air-blast transformers are used and the air conditions are not satisfactory, it would, in our opinion, be advisable to install an air washer.

Resistance Bulbs and Thermo-Couples

For several years it was our practise to install resistance bulbs in the windings of the largest turbo-generators and synchronous motor-generator sets, in order to know at all times the temperature of these machines. The results obtained by their use so far have not met with expectations.

The resistance bulbs furnished to-day are somewhat more substantial than the earlier type but are still too frail to stand much hard usage. In the windings of our more recent motor-generator sets thermo-couples have been installed which we believe, will give better service than resistance bulbs, as they are less liable to mechanical injury.

The temperature indicator has been found very useful in determining when a machine needs a thorough cleaning. Thus, a possible burnout is prevented which otherwise could not be foretold.

It is our opinion that wherever possible thermo-couples should be installed at the hottest points in the windings of all large generators or motors.

Dampers on Air-Blast Transformers

In most of our stations where air-blast transformers are installed a common air chamber is utilized for all the transformers and we have found this method of air supply more economical than to use a separate and independent blower for each transformer. Each transformer is equipped with a top and bottom air damper so that in case of fire in the transformer, the dampers may be closed, thus shutting off the air supply and smothering the fire.

We strongly recommend top and bottom dampers on all air-blast transformers especially where a common air chamber is used. If the transformers are not equipped with both top and bottom dampers and a fire starts in one of the transformers, it is necessary to cut off the entire air supply for a considerable time depending upon how long it takes to put out the fire. This might compel the station man to disconnect the other transformers from the service; thus resulting in a complete interruption.

Coherer Alarm Device

This device is used to register predetermined voltage rises on the transmission line itself, across reactance coils or on aluminum cell lightning arresters. In order to get a permanent record of its action, it can be connected to a relay which will make a record on a multi-recorder. This device has been found very convenient to register the discharges of our aluminum cell lightning arresters.

Previous to the installation of this device, it had been the custom to install with each aluminum cell arrester a discharge recorder which has a continuously moving paper punctured by the discharges. We finally came to the conclusion that while these recorders gave us much desired information, the continual replacement of paper record rolls was expensive and troublesome.

Potential Indicating Devices

Electrostatic potential indicating devices are used to indicate potential on feeder circuits. The instrument is connected to the middle point of two strain insulators in series, which are connected between each live wire and the ground. The displacement current through the insulators is sufficient to operate the instrument.

Another method of obtaining the voltage indications is to install potential transformers whose secondaries are connected to indicating lamps or voltmeters. However, this means is rather expensive and the required space for potential transformers is not always available.

It would therefore seem that the potential indicating device now on the market might fill a long felt want.

Presented at the 33d Annual Convention of the American Institute of Electrical Engineers, Cleveland, O., June 28, 1916.

PROTECTION OF HIGH-VOLTAGE DISTRIBUTION SYSTEMS BY ISOLATING TRANSFORMERS

BY O. O. RIDER

ABSTRACT OF PAPER

This paper calls attention to the practicability of localizing line disturbances by means of transformers. Application is made to high-voltage distribution systems serving the rural communities which results in an inter-connected net work of overhead lines.

IN THE generation, transmission and distribution of electricity there is growing the application of intermediate voltages for the supply of energy to the smaller communities and isolated industrial centers, forming a net-work of high-voltage distribution with characteristics in operation and maintenance that present new problems and require plans for protection differing from those on the low-voltage system used in urban distribution. This development applies more particularly in those sections of the country where the population is generally distributed, such as found in the Middle West.

In choosing an electrical pressure for this work, 33,000 volts has been found to be the highest practicable voltage for pin-type construction, and at the same time a voltage sufficiently low from which small amounts of power can be supplied economically to meet the growing commercial needs. It also appears that a system operating at this voltage is the most suitable intermediate step between very high voltages for delivery of large blocks of power over long distance, and the low-voltage system ordinarily used for distribution in the larger cities.

In the operation of such a system one requirement is at all times preeminent; namely, supplying continuous service over three wires. The non-grounded neutral system is used which permits service being maintained under conditions of accidental ground on one phase. This greatly lessens the chances of interruption by short circuit but, as is well-known, it produces more surges for a longer time during an arcing ground than the

grounded-neutral system. Delta connection of transformers is used.

The chief aim of this paper is to call attention to the improved operation obtained from isolating transformers on a non-grounded neutral system. Other attending factors affecting continuity of service are important and are receiving careful attention, but are not within the scope of this article.

Localization of Abnormal Conditions

The localization of disturbances caused by single-phase accidental grounds is a matter of great concern, especially in high-voltage systems which extend over a large territory. A single defective insulator which grounds a phase affects the entire system which is metallically interconnected. Small or local electric storms often develop in one section and cause this hazard to service in every other section. When the storm is general the entire system is subjected to these abnormal conditions from the time the storm enters the zone of electrical supply until it passes the remote sections supplied from branch lines. The troubles are multiplied accordingly.

In the growth of these large interurban systems small power plants are sometimes connected where the insulation of the line is not up to the highest standard, due to one cause or another. Also, where systems are connected together for interchange of power, the possibility of trouble from accidental arcing ground is multiplied by this extension of territory covered by the two systems. In many such cases it is undesirable to use automatic circuit breakers at the connecting points to disconnect the power when the trouble is due only to unbalanced electrostatic conditions of the phases.

In these cases isolating transformers between the systems can be advantageously used. These transformers may be either 1 to 1 ratio or they may step down the power to a lower distributing voltage and up again to the transmission voltage, according to the attending conditions. It is desirable, of course, to locate these stations where local distributing service is required. Where a section is to be isolated by this means an added advantage comes in the use of standard regulators for the maintenance of voltage. This plan of regulation will be found to care for voltage conditions at intermediate points and eliminates the necessity of supplying a great number of regulators for the small communities

With these isolating transformers the disturbance of an accidental arcing ground on one section is confined entirely to that section, and still power is transmitted without interference to and from all other sections as under normal conditions.

On each section where an accidental arcing ground takes place the proper protective devices should be used to protect from abnormal voltages. The arcing ground suppressor has been recommended and used. It is not the object of this article to treat these details but simply to record the successful use of the isolating transformer which limits the disturbances to one part of a large system.

Discussion on "Studies in Lightning Protection on 4000-Volt Circuits" (Roper), "Experience and Recent Developments in Central Station Protective Features" (Pollard-Lawson), "Protection of High-Voltage Distribution Systems By Isolating Transformers" (Rider), Cleveland, Ohio, June 28, 1916.

E. E. F. Creighton: Of Mr. Roper's paper I will say, first, that I think it is a piece of scientific work on a magnificent scale of very great value to the electrical industry. It differs from most of the work, in that it is finished. The whole electrical industry is benefited, new principles have been proved and some principles have been disproved and discarded. There will be a chance to get better service on the part of those who wish it, and better lightning arresters. From my own standpoint I wish to acknowledge a great benefit derived from Mr. Roper's work in that it made possible to choose between several factors of design of lightning arresters, and thereby improved the product for everybody.

Apparently, from the way in which Mr. Roper has presented this paper, it was a very simple affair, but I assure you that the thousands of data which he has collected were in a very chaotic condition, and it required the highest sort of analysis in order to bring some sort of order out of this chaos. All sorts of antagonistic results were obtained—they are all simple enough now after Mr. Roper has analyzed them and told us why they are antagonistic, and he has been able by that method to discard certain parts and draw proper inferences from other parts.

I want to pass on now to the other papers, not as a discussion, but simply to point out certain factors. Take the next paper by Mr. Pollard and Mr. Lawson—this is a paper of a different character. It is a record of progress with new apparatus. The modest presentation of the subject gives an inadequate idea of its importance.

It seems to me a very good time to bring out the importance of the arcing ground suppressor in the problem of grounding the neutral. This discussion, by silence, yesterday, related to one of the very big interests, the telephone interests, and the possibility of interference between the power circuits and the telephone circuits. The interference, unfortunately, is all in one direction, since the telephone circuits have such a tiny amount of power they cannot in any way interfere with the power circuit.

These are two big public service interests in which we are all interested and which we want to see successful, and this problem is not one for the lawyers, but one for the engineers. If the engineers cannot get together and decide what can be done to minimize the effects of interference, the law court is a poor place to go, and the spirit which has been manifested on the two sides of this particular case—I was able to see it because I was brought in as a third party in the discussion of the value of the arcing

ground suppressor in avoiding interference—gives hope that this interference may be eliminated in the future. There were cases of interference where the telephone girls received very bad shocks from the heavy grounds that were induced in the telephone line, and we were looking for some method of avoiding them.

The greatest cause of interference and the widest spread of interference between power lines and telephone lines is due to electromagnetic induction. Electrostatic induction is very bad in the case of a telephone line being near the power line, for example, if it is placed underneath or on the same pole with the power circuit. However, by placing the telephone line on adjacent right of way, the electrostatic troubles are reduced to a negligible value which the telephone company can take care of without trouble. When, however, we take into account the electromagnetic troubles, it becomes almost impossible to prevent interference. Take this one case of the Public Service Electric Company where the grounding current for the total system is only 60 amperes. The radius or distance over which 60 amperes will influence the parallel telephone lines is rather small. By grounding the neutral, however, that 60 amperes is turned into several thousand amperes, and the distance over which the electromagnetic force will influence the telephone lines is greatly increased.

One of the strongest factors in maintaining a non-grounded neutral system is by the use of the arcing ground suppressor, and if Mr. Osgood should speak on the subject, he could tell you a lot concerning the studies which they have made relative to the interference, and the conclusions they have come to regarding the use of the non-grounded neutral.

The suspension insulator problem is one which will probably not be solved for some time to come. I wish I had the time to note the relations of these big corporations to the solution of the problem. In the case of the Commonwealth Edison Company it takes a broad spirit to come to the conclusion that Mr. Roper gives in his paper—that with all the work that was done, that with all the thousands of dollars that were spent, the direct gain in the saving of dollars and cents was nil. The whole thing turns on the point that it gives better service. In the same way with regard to the investigations of the Public Service Corporation of New Jersey—the service has stood above everything else.

When we come to the insulator problem, we have a number of comparatively small companies building insulators and reducing the price of the insulators at a time when a big corporation would have increased the price and put the difference into experimental work. There is no saving today in having a cheap insulator. If the cost of the insulator could be increased fifty per cent, and it would do away with the line troubles, it would be a great saving to the transmission engineer, but it seems impos-

sible for the smaller concerns to get together and carry on such an investigation.

C. P. Steinmetz: Reverting for a moment to the individual papers, it is interesting and significant in Mr. Roper's paper to note the conclusion that although 100 per cent protection is not warranted because the cost of perfect protection is somewhat greater than the cost of repairing damage to transformers resulting from less perfect protection, nevertheless, he introduced 100 per cent protection as quickly as possible because reliability is the all-important question. Unfortunately, it is not every electrical system which takes that attitude; it is far from being the case. There are, indeed, many that have not reached the high standard which the world will demand in the future, but those which have adopted this standard include I may say, practically all of those operating systems that are the descendants of the old Edison three-wire d-c. system.

In Mr. Rider's paper is another interesting and significant statement, namely, that the non-grounded delta system has been preferred. Now, there are many engineers, especially in the West, whose experience has been different, and who from their experience prefer a grounded Y system of transmission, but the explanation of this apparent difference of opinion is contained in Mr. Rider's paper in the statement that one requirement is at all times pre-eminent, namely, supplying continuous service over the three wires. It is brought out, as sharply as it can be, that the relation between the isolated delta and the grounded Y is that of reliability of service as compared with cheapness, and where it is desired, at the least investment, to get some kind of service, there the grounded wire has the advantage, because with the line insulated to a lesser degree this system gives less trouble. But where reliability first is the predominant feature, as it must be in those great systems which really desire to change the statement, that the good and old reliable is not the electric light, but the tallow candle, there the isolated delta is used.

The pre-eminent importance of a high degree of reliability is present throughout all the arguments of the three papers, and is substantiated to some extent, by experience in establishing and maintaining such reliability. It is in reality a great social problem involving the organizing of a universal power distribution and supply by electricity, different phases of which are severally dealt with in these papers.

Mr. Rider's paper deals with one phase of it, that of country distribution; Mr. Roper's paper deals with another phase of it, that of city distribution, and the third paper deals with station control and system control. But when electrical engineering enters the field of taking over the universal power supply of the community, of the nation, they must then go beyond the old conception of trying to organize so as, with the minimum possible investment, to get the maximum immediate returns, because as soon as they undertake a universal problem, a social

duty also devolves upon them, the duty of giving satisfaction to all.

Then also comes in the problem of not interfering with other lines, with the telephone, etc., and in taking all those precautions that will safeguard life and at the same time give maximum reliability, in short, a conception of organizing the system so that it will be a benefit to all and a harm to none. That is the fundamental requirement which is before us, and which must be the universal conception and practise before we can expect electric power to be used as the universal agent of the world's energy supply.

In closing, I wish to add only one feature to the general discussion dealing with protective devices, provided against abnormal voltage, abnormal current, abnormal frequency, etc., and that is, to mention a further protection against troubles which are encountered, not in the experience with those systems which have been considered today, but rather in other systems, in smaller systems, where economy of installation has predominated, and economy of operation has followed. The troubles to which I refer, the sources of many mysterious interferences with reliability, are carelessness and dirt.

A switch is opened by some assistant operator by mistake, and is immediately thrown in again, before this is noticed. The synchronous apparatus has fallen out of step, or otherwise flashes over, and a mysterious accident has to be investigated by writing theories on high frequency, etc. Or a high-voltage switch bushing, gradually becoming covered with dust and dirt, is located near a window; the window is left open admitting moisture laden air, which condenses on the dirt and a flash-over results; the lightning arrester does not discharge, and the transformer is burned up by a short circuit. Then an investigation shows by factory test that it requires more than three times normal voltage to flash-over that bushing, hence, there was high voltage present. The lightning arrester did not discharge, although only a short distance away, and that means that this high voltage was of such extremely high frequency as not to reach and discharge from the lightning arrester. It results often in a general lack of confidence and uneasiness on the part of the operating staff.

Such things can be avoided only by automatic recording devices which would have shown there was no abnormal voltage and no high frequency present, that the accident started with a short circuit at the bushing, and therefore the bushing was in such condition that normal voltage and normal frequency went over it. In the other instance that I mentioned, the automatic recording device showed that the switch was opened and immediately thrown in again, of which operation there was no record in the station report.

These instances illustrate what I want to bring out—I do not wish to say there are no such things as high-frequency dis-

turbances, excessive voltage, etc. They are often present, and have shown themselves over and over again. They are the most frequent and serious causes of trouble in existence, but do not let us always jump to the conclusion that every trouble is due to some mysterious phenomenon; let us also keep in consideration of the fact that the human element and the fallibility of human nature are involved, which matter is a very frequent cause of trouble, against which there is no remedy except by the use of automatic devices, that are not susceptible to human frailties or neglect, and will not forget to record immaterial incidents.

P. H. Chase: In Messrs. Pollard and Lawson's paper a brief mention is made of the split or divided-conductor principle in its relation to ideal relay protection of transmission circuits. I wish to bring out a few points in connection with the methods used in the application of this principle.

What may be called the individual differential or balance method has been used for some time for the protection of transformers, generators and cables in order to secure perfect selective disconnection of faulty equipment from the system, in the minimum time. This is accomplished by entirely separating the means used for protecting each part, from the means used for protecting any other part of the system, thus making the disconnection of the faulty part contingent only on predetermined conditions within itself.

This method of protection has been utilized to a great extent in England to allow the operation of the transmission system as a true network, which is the only way a transmission system covering a large area can be economically constructed and operated with the minimum liability to interruption. An interconnected system can be operated with a fair degree of freedom from interruption by the use of time-limit relays of various kinds, but this protection at best falls far short of that obtained by the use of the individual differential or balance principle, and is further impaired because, particularly on a large system, the operating combinations are continually changing. As is outlined in this paper, apparatus nowadays does not require the protection, but the integrity of the service demands it.

Contrary to a somewhat widespread impression, the individual differential or balance method of protection does not involve a net increase in cost, considering both investment and operating cost, when applied to a transmission system. An interconnected network allows the greatest utilization of the transmission copper at all times by decreasing power losses and maintaining voltage. Also such consolidation allows the greatest possible utilization of the most efficient generating units connected to the system, and of the diversity factors of the loads in different areas. With an interconnected system, each substation may have several sources of supply, and, in the case particularly of static transformer substations, the operating force may be decreased, or

even eliminated, as there will be automatic selective disconnection of any faulty supply circuit without an interruption of service to that substation. These considerations, it is evident, may greatly overbalance the consideration of a possible greater investment in transmission lines and equipment.

The individual differential or balance method of protection may be applied to transmission circuits by:

1. Running external pilot wires for each line or cable. This method is mainly applicable to short underground circuits.

2. Pairing two lines or cables which have the same destination, and operating them regularly as one circuit, disconnecting it only in case of failure of either line or cable. This method is applicable particularly where existing circuits are to be paired.

3. Dividing each conductor into two parts, which normally carry equal currents. This method is applicable to new cables which are usually called "split-conductor" or "divided conductor" cables.

With particular reference to the split-conductor cable, the means of protection consist essentially of a differential current transformer (or its equivalent) for each phase, the current transformer having two opposed primary windings and one secondary winding, connected to a simple instantaneous overload relay, at each end of the circuit. One primary winding is connected in each split to give balance normally. However, end faults and mechanical and electrical limitations in the insulation between splits, complicate the proposition.

In case there is a fault near the far end of a split-conductor cable, the relay at that end will operate due to relative reversal, and disconnect the cable; the relay at the other end evidently will not be affected unless there is sufficient vectorial unbalance between the currents in the two splits. This unbalance cannot be sufficient unless the impedances of the two paths to the fault are considerably different, or the currents are very large, or the splits are separated at the far end with a split switch. With this limiting condition, the end fault, taken care of, faults at other points of the cable present no difficulty.

The introduction of additional reactance results in the best solution, because any acquired unbalance with end faults can be readily obtained at low values of current. The use of a split switch results in high voltages between the splits, even under normal conditions, and full voltage under fault conditions. The insulation between splits must necessarily be relatively small in order to keep down the size and cost of the cable, therefore, these voltages must be avoided so far as possible.

A further protection may be obtained with reactance, that of insuring against the loss of individual differential or balance protection which might result from a fault between splits of one conductor. The chances of such a fault may be remote, but can be simply guarded against without accompanying disadvantage.

This arrangement of the reactance is called an "end" or "selec-

tor'' reactance, and consists of one small iron core reactance in each split, a total of three reactances being at each end of the cable, which cause the necessary unbalancing between the currents in the two splits with an end fault. From the one-line connection diagram in the figure it will be noted that with an end fault the split currents from the far end are unbalancéd because in one current path there is no additional reactance, while in the other there are two additional reactances.

Under normal conditions each split will carry equal currents, and also there will be a voltage between the splits equal to the drop across one of these reactances, which will cause unequal currents to flow in the splits in case of a split fault. Therefore, the cable will be disconnected in case there is a ground, a phase

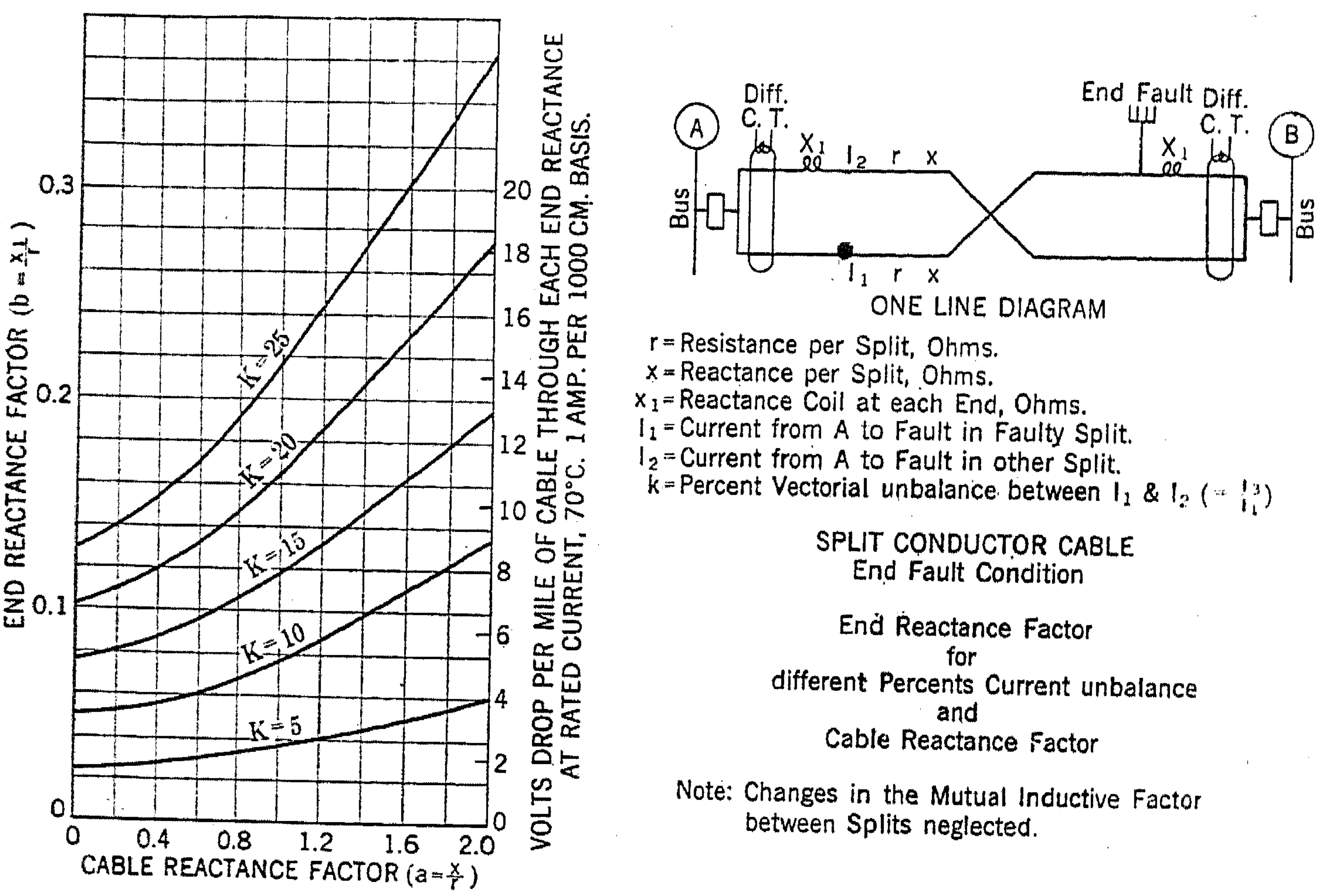


FIG. 1

fault or a split fault, and the selective protection cannot be impaired by changed conditions in the cable without disconnection.

The curves show the relation between the end or selector reactance and the resistance and reactance of the cable for different percentages of unbalance, k, under the end fault or limiting condition. The right hand scale of ordinates shows the end reactance volt drop per mile of cable for the required unbalance at full-load current, on a one ampere per thousand circular mil basis. It is believed that a value of k equals 20, is a fair value to use in present practise, which means that the vectorial unbalance of the currents in the splits is 20 per cent of the larger of the two split currents.

The reactance and resistance per split are respectively double their values per conductor. For 350,000-cir. mil sector cable, 13,200-volts, with $6/32 \times 6/32$-in. insulation, and 5/64-in. split in-

sulation, the 60-cycle reactance factor is about 0.85. The usual values of reactance factors should range from 0.4 to 0.9 at 60 cycles, the larger cables having the greater factor. For all practical purposes it is evident that 25-cycle cables can be considered to have zero reactance. These curves give a ready means of determining the values of end reactance to use for any desired combination.

The differential current transformers should have a close balance between the primary windings, an allowable unbalance of not more than 0.1 per cent being a desirable amount, also the end reactances should have closely similar saturation curves in order not to disturb the inherent balance between the splits at all current values. The splits are transposed in present American practise near the middle of the cable only, but additional transpositions may be made to keep the balance between the splits within 0.1 per cent. This value is not difficult to obtain with present methods of cable construction.

The importance of close balance is evident when one considers the condition of a through fault with a split-conductor cable feeding short-circuit current to it. The value of this current may be as great as thirty times normal. With an inherent unbalance between the splits of 0.1 per cent and an additive unbalance in the differential current transformers of 0.1 per cent, the total unbalance will become 6 per cent with thirty times normal current flowing. This unbalance naturally must be a safe amount less than that for which the relay will operate, in order to prevent disconnection of the cable.

J. T. Lawson: I would like to call attention to the table headed "Classification Troubles." This heading is incorrect and should read "Classification of Interruptions." The table is not a classification of troubles of the Public Service Electric Company, but a list of the interruptions which we were unable to protect against.

Particular attention should be given to the cable failures. As you will see, the cable failures in 1915 have gone up and these failures include those mentioned by Mr. Pollard; namely, the short circuits between phases.

Short circuits between phases in our system up to this time had been very few in number, most of the failures being single-phase grounds.

The failures mentioned occurred on a certain set of circuits used as tie feeders on which feeder reactances had been installed at each end.

We think the installation of feeder reactances at each end of these circuits may have had the effect of confining any high-voltage condition in these cables, thus causing the failure.

Referring to Mr. Creighton's remarks in regard to interference of telephone systems by power lines, I would point out that the interference to the telephone system by any apparatus which we might install would be a serious problem to a power company. Almost all the large power companies have load dispatchers or

system operators who are dependent for their efficient service on the use of the telephone, and any apparatus we might install in our stations which would interfere with the telephone service would seriously interfere with the service which the power company could give by the load dispatcher as he is dependent on the proper working of the telephone wires.

John B. Taylor: Referring first to Mr. Roper's paper, I understand that the system is the four-wire three-phase, 2300/4000-volt with neutral grounded, and this neutral fourth wire is grounded at but one point,—the substation. How is the fourth wire regarded as a lightning risk? Is it provided with arresters?

How are the grounds for lightning arresters made, and is the resistance tested initially or subsequently as a matter of routine?

Regarding the transformer connection boards, which have been removed, it was my impression from reading the paper that the policy of removing them was adopted before the policy of "100 per cent protection." This might mean if the 100 per cent protection had been instituted first, the connection board would not have appeared as the source of so much trouble.

On the paper of Messrs. Pollard and Lawson, I must limit myself to calling attention to what appears a discrepancy between the table "Classification of Troubles," and the statements in paragraphs immediately before and after. The text gives the impression that the various devices have reduced the number of cable troubles, but if I read the table correctly, the figures do not show it. 25-cycle cable failures are listed as 4 per cent in 1913, 5 per cent in 1914, and 26 per cent in 1915, and in the case of the 60-cycle cables the troubles are listed as 14 per cent in 1913, 10 per cent in 1914, and 15 per cent in 1915. Attention may also be directed to the line at the bottom of the table showing yearly "cable failures per mile." It is my impression that the figures do not compare favorably with the cable records on other large systems;—for example, the Commonwealth Edison Company of Chicago, and the Interborough Rapid Transit Company of New York, operating with grounded neutral and comparable voltage. The Institute TRANSACTIONS of several years ago, if my memory serves me correctly, will show failures in the order of one per year for each hundred miles of cable, but representatives of these companies may be able to correct me if in error.* The figures given here are more on the order of one fault for every six or eight miles of cable each year.

This comparison is a pertinent point for consideration. Is this practise of putting a ground solidly on one conductor making trouble, or is there some other explanation of the relatively high number of cable failures?

The troubles on overhead lines have been reduced either by the elimination of poor insulators, the use of arcing ground

*See A. I. E. E. TRANSACTIONS, Vol. XXVI. Page 1614 for Commonwealth Edison Co. 2 burnouts per 100 mile-years. Page 1641 for Interborough Rapid Transit Co. 0.016 burnouts per mile-year.

suppressors, or a combination of the two, but unless I misread the cable figures the record is not good.

J. O. Montignani: The Rochester Railway & Light Company operates outside of its direct-current district a three-phase, four-wire, 4150-volt grounded neutral distributing system, having a total wire length of about 1200 miles, 300 miles of which is underground. We have about 1800 transformers connected to our lines, with a total capacity of 17,000 kilowatts. Previous to the year 1911, we relied for protection against lightning upon multi-gap arresters placed at approximately one-half mile intervals on the more exposed lines. Not only was this quite inadequate protection, but the arresters themselves proved to be a prolific source of trouble and after most lightning storms we usually found it necessary to go out and gather up the charred fragments of a number of arresters. Invariably in burning up, the arresters fused the line wires connected to them, causing very serious interruptions to the service.

During the summer of 1911, when we first began to keep systematic records of our lightning troubles, we lost 99 transformers in thirty-one thunderstorms, being 6.1 per cent of the total transformers then installed. This alarming record decided us to remove all multi-gap arresters from our lines and install outdoor-type electrolytic arresters at exposed parts of the system, and at important junction points on the feeders. This was accomplished in the spring of 1912, and resulted during the summer of that year in reducing our losses to 1.2 per cent with thirty-two thunderstorms. Since that time our annual losses have averaged about 1.5 per cent. That the change was economically justified is shown in the fact that basing our calculations on the reduction of transformer losses from 6.1 per cent to 1.5 per cent, the annual saving in transformers and estimated current sales amounts to a little over $2000, after allowing for interest, depreciation, and maintenance of the arresters. We have not lost a single electrolytic arrester during the four years they have been in operation, and that they are draining our lines of many severe lightning disturbances is well proven by observations we have made.

As compared with the Chicago system, our transformer losses are still very high, but the cost of electrolytic arresters would make prohibitive much further extension of that type of protection. On the other hand, we have got to be satisfied that the installation of a large number of less expensive arresters is not going to introduce greater risk of service interruptions due to their burning up, even though the loss of transformers is reduced thereby. Mr. Roper makes no mention of the number of arresters destroyed annually, and I would like to inquire if he has any record of such loss and consequent interruptions of service. I have spoken with several central station engineers whose experiences have led them to disagree with Mr. Roper's statement that:

"Modern types of arresters comply with the specification that a protective device must be less subject to troubles than the apparatus which it protects."

The results obtained in Chicago by removing the terminal boards from transformers are very interesting and show conclusively that this is a most vulnerable point of the transformer. Our experience in Rochester has been that about 50 per cent of transformers damaged by lightning have had the primary leads burned off due to flashing-over at the terminal board. It would seem, however, that inasmuch as the terminal board serves the useful purpose of supporting and separating the leads as well as facilitating changes in connections, a remedy for its lightning troubles might be found by redesigning terminal boards to provide greater dielectric strength.

R. F. Schuchardt: Too much emphasis cannot be given to the words of caution which have already been spoken with reference to interpreting information based on experience. One must always keep in mind the essential details of the system on which the experience was obtained. For instance, reference is made in this paper to the aluminum cell arrester reducing cable trouble. This reduction is undoubtedly due to the fact that a part of the transmission system consists of overhead sections connecting to underground cables. A few years ago Dr. Creighton made an exhaustive study of the Commonwealth Edison Company's transmission system, which is almost entirely under ground, to see whether there were any surges going on in that system which might be avoided by the use of aluminum cell arresters. The conclusion arrived at at that time was that we were not justified in installing such arresters.

The connections of the Essex power station seem rather unduly complicated. I do not see why the great flexibility of the old series arc system is necessary in a high-tension generating station even when supplying a system as extensive as this.

I want to say a word in reference to Mr. Rider's paper, that consideration must be given to the kind of system to which you want to apply the isolating transformer. Undoubtedly, in many cases, for instance, in a city or village where step-down transformers must be used, it may be advisable to step-down and then to step-up again, thereby getting the isolation and also the additional advantage of regulation on the outgoing line. Or where an existing line, perhaps of inferior construction, is purchased and it is desired to connect it to the system, an isolating transformer may be preferable to wholesale reconstruction of the line: but it cannot be expected to serve as a general panacea for the ills of overhead lines. It may many times be cheaper to weed out the weak spots on lines rather than to put in the rather complicated installation of an isolating transformer with its necessary protective devices.

Peter Junkersfeld: I would like to offer a word of caution against over standardization. I refer particularly to Mr. Roper's

paper. That development and investigation in Chicago cost us, not thousands of dollars, but many times tens of thousands of dollars. The conditions there were such that we felt, however, that this particular expenditure of money in that direction would do more in the way of further improving the service than if it were spent in some other direction. The thing which was good engineering in that case maynot be good engineering in some other cases. In fact, similar large refinements in service in other communities in that general section of the country might be undesirable. It is an old saying that you must cut your coat according to your cloth, and the coat must fit the individual. The trimmings on this coat of electric service must fit the community served. In this case it was considered better to put a little more quality in the electric coat than to decrease the price. In many other communities that condition might not prevail, and that point should therefore be emphasized.

David B. Rushmore The report which we have heard gives us the result of a scientific examination of operating conditions. This is a great advance over anything which we have had in the past and offers great promise for future study. In order to make an investigation thoroughly scientific, the factors must be known quantitativelyas well as qualitatively. This means that sometime in the future we must understand the quality and magnitude of the lightning disturbances involved.

With all its disastrous results, it is interesting to know that lightning is of some benefit. It is estimated that at least one hundred million tons a year of nitric acid are formed by the lightning discharges, and this is carried to the earth by the accompanying rain. On this source we are very largely dependent for the supply of nitric acid which is such an important part of the food of vegetable life and, indirectly, of animals.

D. W. Roper: We do not use the neutral wire for overhead lightning protection. Our neutral is grounded at each substation. At each transformer where an arrester is installed on the outer wire, an arrester is also installed on the neutral wire. A ground rod is used for the ground connection. In Chicago, there is no difficulty in securing good grounds as the water level is only a few feet below the ground level.

The load in Chicago on the underground cables does not operate quite as well as the figures given by Mr. Taylor would seem to indicate, but excluding burnouts due to external causes, such as a pick being driven into a cable or some other similar disturbance, the faults in the 9000-volt cable average from two to four per hundred miles per year.

N. S. Diamant: I would just like to touch on the question of sudden short circuits. The authors speak of "the maximum short-circuit current" that will flow into a fault, and they give the curves of Fig. 4 to further illustrate this point. Now, I take that by "maximum short-circuit current", in per cent of the full-load current, the authors wish to refer to the most unfavorable

condition possible which will take place if the sudden short circuit were to occur near the zero point of the e.m.f. wave. In this case the current will overshoot and reach nearly twice the value it would have if the short circuit were to occur very nearly at the maximum point of the e.m.f. wave. It seems to me—although it is not clearly stated by the authors—that in Fig. 4 they have given us the most favorable condition of a short circuit under the assumption of ideal machines (of 15 per cent reactance each) with no damping effect. This damping may be roughly taken into consideration, if desired, but in any case I think that it is best to refer the curves and the discussion of a short circuit to the worst possible condition. This point should have been made clear by the authors: thus according to my interpretation of the connection of the six alternators under consideration, the rush of current with 5 per cent tie-bus reactance per generator will be anything between 30 and 60 times full-load current—rather than 30—under the ideal condition of no damping. Similarly for the other points of the curves.

H. Mouradian (communicated after adjournment): Mr. Roper's contribution appears to be the first published report of a systematic attempt to study the lightning problem experimentally in the field (rather than in the laboratory), where, it seems to the writer, the problem must receive its ultimate solution.

A study in the field, along somewhat similar lines, has been conducted by The Bell Telephone Company of Pennsylvania during the period 1911 to 1916, this study comprising the observation of lightning effects as influenced by various degrees of protection upon the telephone cable plant in the entire state of Pennsylvania, the entire state of Delaware, part of the state of New Jersey, and certain sections of the states of West Virginia and Ohio. This study included the observation of lightning effects as associated with approximately 25,000 cable pairs, fully protected by means of open space cutouts, and, roughly, 500,000 telephone stations.

As Mr. Roper's paper relates to transformer protection, and the data collected by The Bell Telephone Company of Pennsylvania relate to cable protection, this discussion will only consider some of the broad points involved in the field observation of lightning effects.

As noted by Mr. Roper, "the variations of the lightning itself overshadow the rest of the variables." This is borne out by our experience. In the western half of the state of Pennsylvania, the number of substation arrester operations varied from a maximum of 11,594 operations in 1912 to a minimum of 2962 operations in 1915, a variation in lightning activity of approximately 400 per cent, no change whatever having been made in the type of substation arresters in the meantime.

In reference to the extreme irregularity in the distribution of lightning effects, it appears to us, in view of this feature, that only

through observations covering a large area carried out over a considerable number of years, will it be possible to secure reliable data. Our experience to date has been such that the writer can unqualifiedly endorse Mr. Roper's conclusion 12, to the effect—"Great care should be used in attempting to draw general conclusions from the experience obtained from a few arresters or during a single season, or from a limited area." It seems best to make no changes in the protection practises in a given area, and to carry out the work of observation for possibly five or six years before drawing final conclusions.

In reference to the two other methods of observation indicated in Mr. Roper's paper, first, the study of the trouble caused by lightning in relation to the number of lightning storms, and, second, the study of the relation of fuse troubles to transformer burnouts,—we have found the first mentioned method very unpromising in our work. As regards the second method, our experience with fuse operations, as compared with other lightning troubles, is that the fuse operations appear to bear a closer relation to the intensity of lightning storms than other types of troubles caused by lightning, such as breakdowns in insulation, particularly in telephone work where practically no power current will follow the path of the lightning current.

The writer would like to suggest that Mr. Roper is probably incorrect in his deduction in section IX of his paper, "Increasing the Size of Transformer Primary Fuses," that increasing the size of fuses from five amperes to twenty-five amperes would not materially change the number of fuse operations.

One other point of similarity, which may or may not be accidental, is in reference to the reduction in fuse operations in 1915 as compared with the fuse operations in 1913, shown on Fig. 13 of Mr. Roper's paper. In the state of Pennsylvania, the number of telephone substation fuse operations decreased from 11,546 in 1913 to 4,975 in 1915, the fuse operations being intermediate (6,913) in 1914. There has been no change in our substation protection practises in the same interval of time. It is very possible, therefore that a large part of the reduction in fuses blown (to explain which reduction certain hypotheses have been made by Mr. Roper) may have been simply due to the difference in the character of the 1913 and 1915 lightning seasons. It may be of interest here to note that the telephone substation fuses in use, associated in series with the substations open-space cutouts, wired in ahead of these cutouts, viz., towards the line side, are rated as 10-ampere capacity. As pointed out by Mr. Roper the difficulty of reaching accurate conclusions is very great, and the observer has to be continuously on guard not to ascribe to improved practise what may be simply due to absence or difference in character of lightning.

The writer would also like to suggest that Mr. Roper's last conclusion may be considerably in error, and that if Mr. Roper should continue his interesting experimental work, without fur-

ther changes in the protection conditions of the 4,000-volt transformers, the future may show a very material increase in the ratio of the percentage of transformer burnouts in the class A areas to the percentage of transformer burnouts in the class C areas.

One detail point seems worth referring to. It appears to the writer that the data presented in Mr. Roper's paper indicate, if the difference in the character of the lightning seasons is not taken into account, that the increase in the ratio of arresters to transformers should be credited with a larger percentage of responsibility than the 20 per cent indicated in Mr. Roper's summary, probably as high as 50 per cent. This thought is suggested by the study of Table VIII and Mr. Roper's own statement, in regard to this same table, that "the percentage of fuses blown in class A is less than one-third of that in class C."

Another thing the study of Mr. Roper's paper suggests, and about which the writer would like to secure Mr. Roper's opinion is whether, considering the question purely from the standpoint of lightning protection, the troubles from blown fuses would not be materially reduced, if the grounds at the substations on the neutral wires were removed.

N. L. Pollard: Replying to Mr. Taylor's question concerning the increase of cable troubles as indicated by the table, will say that the total number of troubles per mile of cable and overhead lines has decreased for the 60-cycle system but has increased slightly for the 25-cycle system. The slight increase on the 25-cycle system is undoubtedly due to the fact that we have not installed on this system the protective apparatus to the extent that we have on the 60-cycle system.

The failures on the 60-cycle cables alone, increased materially in 1915. This, we think, may be due partly to the installation of feeder reactances on both ends of the tie feeders connecting our City Dock, Marion and Essex Stations. Since the installation of these reactances, the nature of the cable breakdowns has changed from a single-phase failure to ground, to a breakdown between phases. The majority of the cable breakdowns has occurred on the tie feeders equipped with these reactances and we are led to believe that the installation of the reactances must have some bearing on the breakdowns.

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MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS

BY F. L. HUNT

ABSTRACT OF PAPER

This paper gives the results of megger tests made on disk insulators on a 66,000-volt transmission line in central Massachusetts after 2.5 years' operation. In one lot of 4410 insulators tested 9.77 per cent tested less than 2000 megohms. The percentage of failures in different positions in the string is given on both strain and suspension towers. The actual cost of making these tests under different conditions of weather and of service requirements is given per insulator on the line, per bad insulator and per tower. The cost per insulator on the line, of testing only, varied from 7.3 cents to 11 cents. The cost of replacing bad insulators was 74.5 cents per bad insulator, not including the cost of the replacing insulator.

Laboratory tests made on 30 of the bad insulators taken from the line showed that those which measured very low by the megger fail on 60-cycle tests much below spark-over value, while those with medium high resistance may reach flash-over value and then puncture within one minute. Some insulators which show infinite resistance by the megger, and which withstand arc-over potential at 60 cycles, will fail under high-frequency test immediately.

DURING the latter part of 1915, megger tests were made on all the insulators on one circuit, and part of the insulators on the other circuit, on nineteen miles of 66,000-volt, double circuit transmission line in central Massachusetts. These circuits are supported on galvanized steel towers, three wires to each circuit spaced 10 ft. (3m.) apart vertically, the two circuits spaced 18 ft. (5.4 m.) apart horizontally, the bottom wire 45 ft. (13.7 m.) from the ground, average span, 550 ft. (167.6 m.)

The total number of insulators tested on this line was 4410. These were suspension type insulators hung with four per wire on suspension towers and five per wire on dead end towers. Numbering the insulators from 1 to 5, beginning at the cross arm, the number of failures in each position is shown in the following tabulation.

Strain towers.					
Unit number	1	2	3	4	5
Total number	486	486	486	486	486
Total damaged	50	43	47	51	64
Per cent damaged	10.28	8.84	9.67	10.49	13.16
Standard suspension towers.					
Unit number	1	2	3	4	
Total number	495	495	495	495	......
Total damaged	61	32	47	36	......
Per cent damaged	12.32	6.46	9.49	7.27	......

The above results seem to indicate that there was no logical relation between the number of failures of the insulators in any given position and their distance from the conductors.

Cost of Tests

It was necessary in testing these insulators to take one circuit at a time, so that all the towers had to be gone over twice. Of the total number of 4410 insulators tested, there were 2430 dead end insulators, of which 255, or 10.5 per cent, were bad; and 1980 suspension insulators, of which 176, or 8.9 per cent were bad, as indicated by megger tests above.

A crew of three men was used in making the tests and twenty week days and twelve Sundays were consumed.

The total cost of the tests, including cost of transportation, was $424.69.

The insulators on one circuit were tested on 180 towers and on the other circuit on 69 towers. The cost per tower per circuit on the first 180 towers was $1.97. The cost per tower per circuit on the 69 towers was $1.02 each. The average cost of the whole job was therefore $1.70 per tower per circuit, and 9.6 cents per insulator tested, where only one circuit could be tested at a time with the other circuit alive during the testing.

The variation in cost per tower in the two parts of the job was due almost entirely to the difference in weather conditions. In the first case the weather was cold and the insulators were covered with frost, so that the work could not be started until about ten o'clock in the morning. The men were also stopped several times by rain, so that considerable time was lost, and this section of the testing included most of the Sunday work.

The total cost of replacing the 431 bad insulators was $322.27 or 7. 3 cents per insulator on the line and 74.5 cents per bad in-

lator. The total labor cost of testing and replacing bad sulators on the line was therefore 16.9 cents per insulator of e total number or $1.73 per bad insulator. This does not ver the cost of new insulators. If it had been necessary to y for new insulators, the total cost per bad insulator would ve been three times the original cost.

These insulators were in use less than three years, having en installed in the early part of 1913, put into operation in ay, 1913, and tested in the latter part of 1915.

A recent inquiry made from an insulator manufacturing mpany brought out the fact that they would add 4 cents per sk to the price of the insulators in order to cover the cost to em of putting their insulators through a high-frequency test fore shipment. If such a test would have taken out the insutors that have failed during the first 2.5 years of operation, it ould appear that 4 cents additional in the initial price would ve been a good investment, since the cost of testing and reacing bad insulators has amounted to 16.9 cents per disk on e line.

Another section of line of about the same length upon which sulators of a different design had been installed, was tested at cost of 7.3 cents per insulator, which is slightly less than the st per insulator in the first case. Due to the fact that both circits were tested at the same time, each tower had to be climbed t once. The insulators in this second case showed less than e per cent of failures and, on this account, it was not considd necessary to replace the bad insulators, since there was no se in which more than one bad insulator occurred in one string.

LABORATORY TESTS

To get definite information regarding the nature of the faults the insulators they were shipped to a laboratory where the lowing tests were made with the co-operation of Mr. E. E. F. eighton and Mr. P. E. Hosegood.

The total number of insulators selected was 40. Thirty-five of ese were taken from the line and five were new insulators. venty-one measured below 10 megohms, eight measured 22 to megohms, one measured 220 megohms, five from the line easured infinity, and the five new insulators measured infinity, aking up the total of 40.

Test 1. Eleven of the insulators which meggered below 10 egohms had 60-cycle voltage gradually applied to them until ey punctured. Not one of them reached flash-over value.

The voltage was very gradually raised and the lowest puncture voltage was 22 kv., the highest was 52 kv., and the average of the 11 was 39 kv.

Test 2. Seven of the insulators which measured between 22 and 52 megohms and the one measuring 220 megohms had arc-over voltage applied to them until they punctured. Four of them punctured immediately, 2 of them punctured in one second, one in four seconds, and one in thirty seconds. There is no relation between the megger readings and the time of puncture.

Test 3. In this test a constant voltage far below the arc-over value was applied until puncture occurred. Seven insulators measuring below 10 megohms were tested. The first five had applied to them 20 kv. They punctured in from one to thirty seconds. Two more were tested at 15 kv., one puncturing in one second, the other in six seconds. There is no consistency between the puncture voltage and the megger readings as sufficiently illustrated by the last test. In this test one of the insulators measured three megohms and the other below one megohm, but the higher resistance insulator took one second to puncture whereas the other insulator with lower resistance took six seconds to puncture.

Test 4. Spark-over voltage of 60 cycles was applied to the 10 insulators which measured infinity. Three of these punctured in less than 45 seconds. This is 30 per cent loss on 60 cycles.

Test 5. The remaining seven insulators which had shown O.K. on a minute's test on 60 cycles at flash-over voltage, were next tested on the oscillator using a frequency of approximately 200,000 cycles per second. Flash-over voltage only was applied. Two of the seven punctured in less than one minute. This is again about 30 per cent of the insulators that were left. The remaining five withstood super-spark potential of 120 kv. for 10 seconds each.

Conclusions. The results of these tests are similar to others that have been made and show, first, that insulators which measure very low will fail almost immediately on a 60-cycle test voltage, much less than spark-over value. Insulators with medium high resistance may reach flash-over value of potential and will puncture within a minute. Insulators of infinite megger reading may have faults developed by the arc-over potential within one minute's application. After the faulty insulators have been eliminated by the 60-cycle test, still further faults are found by the oscillator.

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EXPERIENCES IN TESTING PORCELAIN

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

The paper gives the results of numerous experiences in testing porcelain insulators particularly in regard to porosity, absorption of water, surface leakage and dielectric losses. Considerable energy is required to drive moisture out of a porous insulator and it has been found best to restrict the oscillator testing to dry porcelain, whereas the wetter the porcelain the more effective is the 60-cycle test.

THE FOLLOWING experiences in testing porcelain insulators and the resultant deductions are given as an addition to the development of the relating science and practise.

For the present purposes the resistances of insulators may be classified as follows.

1. Distributed resistance due to water in pores.
2. Concentrated resistance due to water in cracks.
3. Surface leakage (external).
4. Dielectric losses (equivalent resistance).

I—DISTRIBUTED INTERNAL RESISTANCE

Wet-process porcelains have been examined having a porosity much less than 0.01 of one per cent by weight. Dry-process porcelains have a usual porosity of 1 per cent to 2 per cent. The pores are fissures, visible to the naked eye if a stain is used to color them. These porcelains take up water rapidly simply by soaking an hour. As the porosity decreases the water meets more and more opposition to its entrance by the back pressure of the air entrapped in the pores. Under conditions easily reproducible in the laboratory a porous body covered with a liquid will remain perfectly quiescent for a minute or two while the liquid is soaking in from every side. Finally the internal air pressure becomes great enough to break through the wall of water and a stream of bubbles will break forth. Where the porosity is very small the porcelain, soaked for months in a bath of water, refuses to take up the water. Still this same insulator on a transmission

circuit will take up sufficient water to reduce its internal leakage resistance to as low as 300 megohms. This difference in absorption is due to the changes in temperature. An increase in temperature causes an expansion of air which drives some of it out. Subsequently it breathes in moist air and moisture. Each temperature change causes a deeper penetration until, by fractional distillation, there is a conducting path between surfaces. The necessary period in such a case may extend over several months.

Such slightly porous and wet insulators still retain some value as insulators but they are a menace since they will fail rapidly under an increase in potential. Such an increase may take place suddenly by the failure of another unit in series with it.

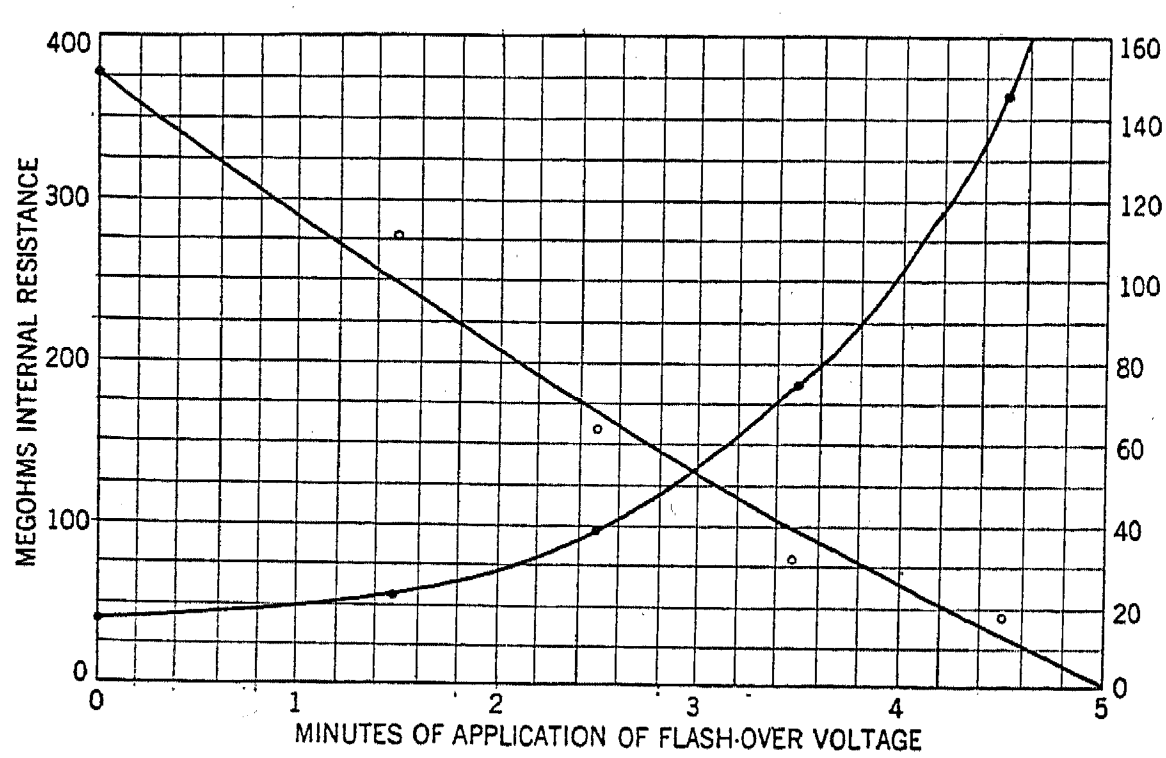

FIG. 1

A rare case of porosity was studied. Fig. 1 shows the relation of internal resistance and wattage loss, both relative to the time. On the application of 60-cycle potential, at flash-over value, the resistance gradually decreased from 380 megohms to zero in five minutes. The wattage rose from 16 watts, slowly at first, then with a rapid increase as the water and porcelain were heated up by the ohmic loss ($E^2 \div R$). At the end of 4.5 minutes the loss was 145 watts. At the end of 4.5 minutes the total energy given to the insulator was 14,000 joules. An unknown portion of this energy was radiated and conducted away during the four periods of interruption of potential test, to measure the ohmic resistance. Calculating the maximum possible temperature, from the energy loss and the specific heat, it must have been less than 80 deg. cent. at the instant of puncture of the porcelain. The

estimated energy was 20,000 joules including the heat conducted and radiated away. A continuous application of potential would have shortened the period before puncture occurred. It is seldom that a porous insulator withstands application of flash-over potential for even one minute.

With even distribution of moisture throughout the head of the insulator and taking 140 cu. cm. as the volume under stress, the average energy per cubic centimeter to cause puncture was approximately 143 joules.

In testing such porcelain for porosity the methods which have been previously recommended are inadequate. The following precautions are taken to get greater accuracy.

1. Evacuation of the porcelain at a micron of pressure or less is carried on for about eight hours.

2. The air is removed from pure water by boiling and evacuation.

3. Water is poured over the porcelain samples without breaking the seal.

4. Subsequently the seal is broken and the samples are allowed to soak a week in water.

5. The surface of the samples is carefully and quickly dried and the weight taken. The error of weighing is not greater than 1 in 100,000.

On samples of low porosity this method may put five-fold more moisture in the pores than the method previously recommended.

II—Concentrated Resistance

Concentrated moisture in cracks or spots causes a rapid rise in temperature and consequently there lapses a brief period before puncture. A crack a mil wide (0.0025 cm.) 2 cm. long and 2 cm. deep would have a volume of 0.01 cu. cm. and the time to cause puncture at flash-over voltages might be no greater than 0.01 second, assuming the specific resistance of the water to be one million ohms. At any rate the period would be brief.

As a rough method of analysis it may be assumed in general that insulators are porous which on measuring less than 600 megohms, withstand for many seconds a potential nearly equal to flash-over value. On the contrary, insulators which puncture quickly are either cracked or possibly porous in a local spot.

III—Surface Leakage

The resistance to surface leakage will depend, evidently, on the thickness and nature of the deposited material on the surface

of the insulator. Using a thin layer of washed clay and varying the humidity, the curves of resistance versus humidity are given in Fig. 2.

The following is a record of one insulator of several which were coated with dust (porcelain slip) and placed in a wooden box where the humidity was gradually increased to a high value and then decreased. The total period of test was 20 days. Surface resistance tests were made from time to time. Fig. 2 shows the relation of surface resistance to humidity in the box. Naturally there was a little lower resistance on increasing the humidity than on decreasing it due to the fact that the humidity was introduced by heating water in a receptacle placed underneath the box and connected to it by means of a tube. The variation in resistance on the up-curve and down-curve, however, is not very great except at extremely high humidities where there is comparatively little interest. This curve may be considered the extreme condition in dusty countries where there is a long dry season so far as rain is concerned but where fogs and dews take place. If an insulator is in service, the leakages of current over the surface would give sufficient heating effect to prevent the lowering of the resistance to the very low value obtained in these tests. These conditions might exist, however, where the line is out of service for testing purposes.

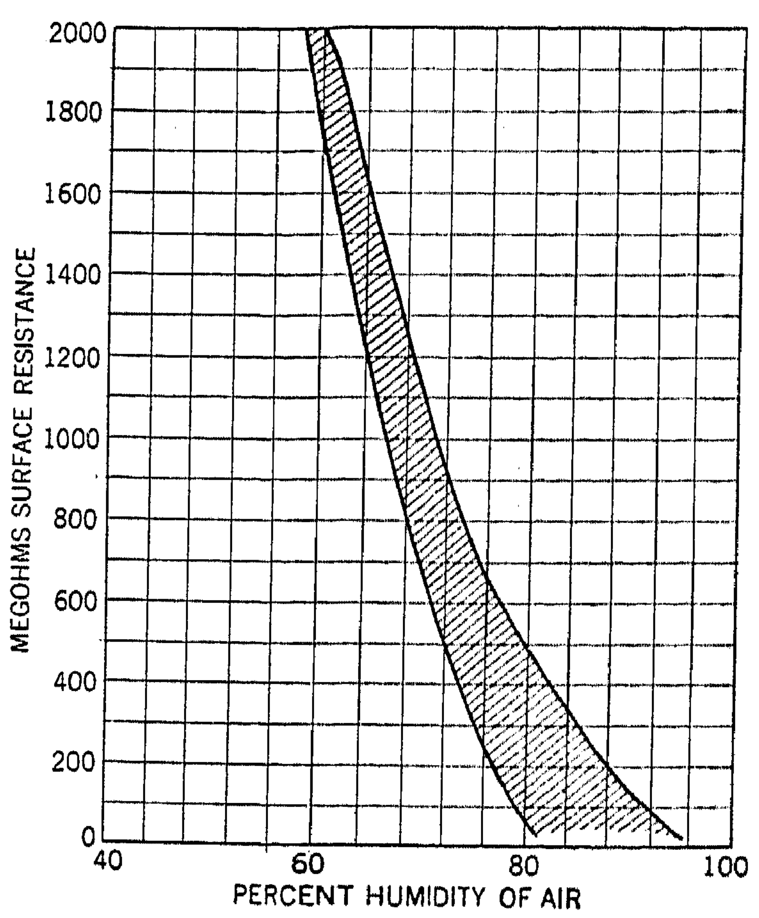

FIG. 2

Naturally the condensation of moisture on a surface of this kind depends on differences of temperature between the insulator surface and the surrounding atmosphere and also upon the humidity of the atmosphere. No attempt is made in the tests to take this factor into account but it is of course the condition which appears so prominently at sunrise.

Increasing the size of an insulator does not necessarily increase its resistance. On the contrary, the larger insulators, due to their shapes, usually have a less surface resistance than the smaller insulators, other things being equal. The tests correspond with the theoretical calculations.

A little salt or carbon added to the film of dust, lowers the surface resistance below the values given in Fig. 2 at the same degree of humidity.

The following tests were made to determine how long it takes a dusty insulator to dry off. A large pin-type telephone insulator was coated with porcelain slip, containing no free acid or alkali. The resistance of the surface coating of clay was initially 88,000 ohms. The insulator was allowed to stand in an atmosphere which had a humidity of 36 per cent and a temperature of 23 deg. cent. The porcelain slip was at the same temperature as the room. After half an hour the moisture had sufficiently dried off the surface of the insulator to give 300 megohms resistance. At the end of another half-hour, making a total of one hour, the resistance had risen to 2000 megohms.

IV—Dielectric Losses

The losses in solid porcelain, for intermittent wave trains, are negligible. The dielectric hysteresis of air is too small to measure. However, if the entrapped air in porcelain is strained beyond its electric strength it forms hot corona, which not only destroys its own dielectric strength but also damages the cell walls of porcelain which enclose it.

The Practise of Testing with the Oscillator

Factory practise calls for oscillator tests on the porcelain parts as they come from the furnace. The parts should not be partially immersed in water for the tests as is usually done in testing at 60 cycles. Caps and pins may be loosely applied to the porcelain, and the corona at high frequency will satisfactorily fill the intervening air spaces. The high frequency and the higher test voltage obtained in the oscillator method of testing finds, on an average, 8 per cent more faulty porcelain than the 60-cycle method. Occasionally where porcelain is only slightly porous and dry, it easily withstands the 60-cycle test and the oscillator has removed as much as 25 per cent of the number that have passed the 60-cycle test. The 60-cycle method becomes more effective if the porcelain is porous and wet. For this reason in testing line insulators the oscillator as recommended in a previous paper must be somewhat modified. It is necessary to make the tests, first with 60 cycles to eliminate the wet porous insulators; then with high frequency to find the dry porous and otherwise weak ones. In applying the 60-cycle test, time

is saved by applying the voltage to all the disks of two strings simultaneously.

It has been shown that the energy necessary to drive out the moisture in a porous insulator is considerable. The oscillator has extremely high power but the wave trains die out quickly. It is, therefore, necessary to restrict the oscillator to the testing of dry porcelain. The wetter the porcelain the more effective the 60-cycle test and the drier the porcelain the less effective the 60-cycle test and the more effective the oscillator test in detecting porous porcelain. Even if there were 100 oscillations in each wave train the potential would be applied only about 1/20 of the time. In other words, the I^2R loss in the leakage of the insulator would be less than 1/20 of what it would be at 60-cycles at the same voltage. Consequently it will take a much longer time to heat up the water in the pores of the porcelain than with an equal 60-cycle voltage.

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A NEW METHOD OF GRADING SUSPENSION INSULATORS

BY R. H. MARVIN

ABSTRACT OF PAPER

Attention is drawn to the known disadvantages of the uneven distribution of voltage in long strings of disks. The general theory showing how the distribution is determined by the various capacities of the units is given. It is shown how the distribution can be improved by grading, or varying the internal capacity of the units.

The proposed method of grading consists in placing flat metal rings on the insulator, around the cap and stud respectively, the porcelain disk being enlarged for this purpose.

A simple method of measuring the voltage distribution is described using a single needle gap.

The results of tests with and without grading are given, the graded strings showing a decidedly better distribution of voltage.

INTRODUCTION

THE UNEVEN distribution of voltage along a string of suspension insulators is well known. With a small number of units this feature is not serious, and scarcely justifies the complication and expense required to overcome it. But with an increasing number of units, the distribution becomes continually poorer. A limit is soon reached where additional units make no appreciable increase in the potential of flash-over. It is believed that any further increase in operating voltages will necessitate a consideration of this problem.

In general, the unit next to the line has the largest proportion of the voltage across it, the succeeding units taking a smaller and smaller amount. This is unsatisfactory for two reasons; the units near the line have to stand an excessive strain, the units near the tower or grounded end have a lower voltage across them than is desirable for efficient service.

A number of plans for improving the voltage distribution have been suggested. These all consist in varying the electrical characteristics of the successive units in a definite manner, and a string of insulators so arranged is said to be graded. The

object of this paper is to describe a new method of grading, and to show some results obtained with it.

Before proceeding it is advisable to give a brief discussion of the fundamental principles involved in grading a suspension insulator.

Theory of Grading

The distribution of the impressed voltage along a string of units is determined by the relations among the four groups of capacities involved. (1) The capacity through the porcelain between the cap and stud of each unit, which may be called the internal capacity. (2) The capacities between the metal fittings and the earth or grounded objects. (3) The capacity from a metal fitting on one portion of the string to any other portion of the string. (4) The capacity between the metal fittings and the line wire. In theoretical discussions only the first two groups are usually considered, but experiments indicate that the others have an appreciable effect.

Considering the first three groups only, the capacitances in a string of units may be represented as in Fig. 1. For the sake of clearness, only part of the capacities between the various parts of the string are shown.

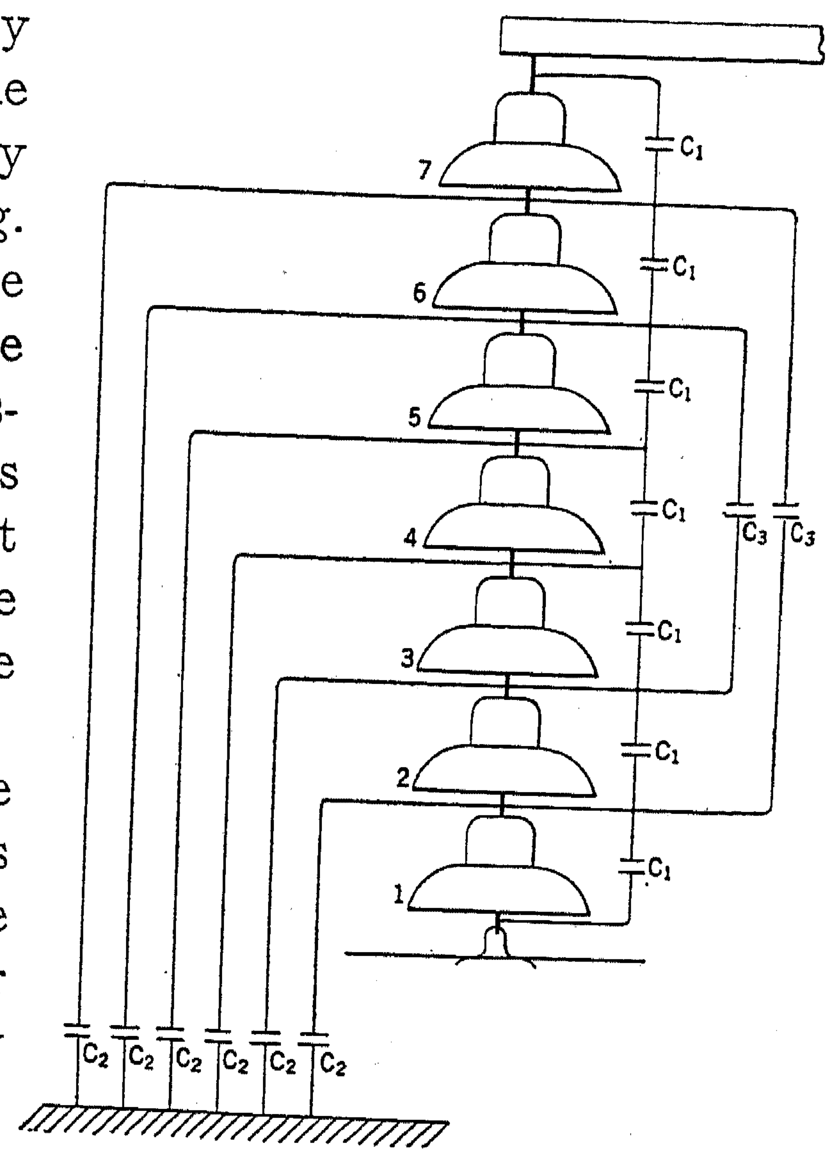

Fig. 1

It is readily seen that the current to charge all the capacities C_1, C_2 and C_3 must pass through the internal capacity C_1 of unit No. 1. The internal capacity C_1 of unit No. 2, has to supply current to the succeeding C_1 capacities, but has a smaller number of C_2 and C_3 capacities to charge. Consequently the first unit has a higher voltage across it than the second. The same reasoning applies to the other units. It appears, therefore, if we neglect the C_3 capacities, that No. 7, the grounded unit, will have the lowest voltage across it. The capacities C_3 tend, however, to make the voltage across the

middle unit the lowest, so that the total result is that one of of the units near the grounded end, and not the grounded unit, has the lowest voltage across it. This will be seen in the experimental curves to be described later.

The principle of grading consists in varying the internal capacity C_1 from unit to unit, so that the voltage across each unit is kept as nearly as possible the same. This means that the unit next to the line must have the greatest internal capacity, C_1, and successive units, decreasing amounts.

Method of Grading Adopted

To obtain the necessary variation in the capacity from cap to stud, the following plan was devised. Sheet metal rings are placed around the cap and stud where it is desired to increase the internal capacity. By varying the width of these rings, the capacity can be varied over a considerable range. Of course the external capacities C_2 and C_3 of the unit are also varied by this, but not in the same proportion as C_1. To secure a perfectly

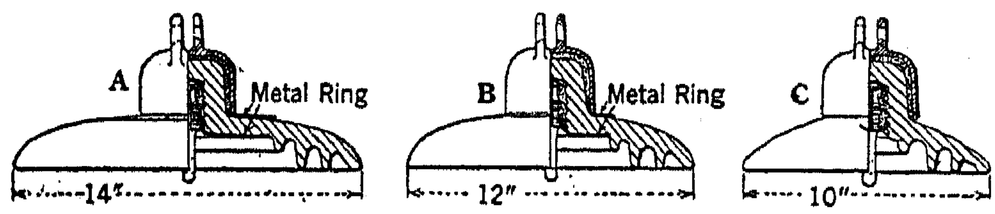

Fig. 2

even distribution of voltage, it would be necessary to have each unit different, entailing great complication, and rendering manufacture very difficult. It was therefore decided to make a compromise, and divide the string into two, three or more groups, each group having different characteristics from the others.

Fig. 2 shows three different sizes of units designed for use in a three group string. On account of the width of the metal rings, it is necessary to increase the diameter of the porcelain so as to give the correct flash-over voltage. The metal rings are stamped or spun out of sheet metal. They are held in place by the cap, and by the cement around the stud. A string would be composed of a certain number of A units next to the line, followed by a number of B units, while the rest of the string to the tower end would consist of the plain C units.

Measurement of the Distribution of Voltage

Before proceeding with the results obtained, it is advisable to give a brief description of the method of investigation.

It is evident that a flash-over test is useless as an indication of the strains at normal voltage, due to the equalizing effect of the corona preceding the spark. Some method must be used in which only the normal voltage is applied. Several very ingenious forms of potentiometers have been devised by Prof. Ryan for this purpose. Conditions, however, did not permit of using one of these, and the following method was therefore devised. While it cannot be considered an exact method due to several inherent sources of error, it is thought to be sufficiently accurate to give a satisfactory idea of the distribution. It has the advantage of being very simple, and requiring very little apparatus.

A small needle gap is provided having the minimum amount of metal in the parts in order to keep the capacity as low as possible, Fig. 3. In our experiments the gap was about $\frac{1}{4}$ in. (6.3 mm.). This gap is placed across each unit in succession and the total voltage across the string which causes the gap to go over is noted. The gap setting is kept the same throughout the test. See Fig. 4. The discharge across the gap is only the charging current of the insulators, and does not injure the needles, so that the same needles can be used throughout. In general, we wish to know what percentage of the total voltage is impressed on each insulator, and the percentage of the voltage across each unit in terms of that across some particular unit. It was found most convenient to base results on the line unit, as in all our work it showed the greatest voltage.

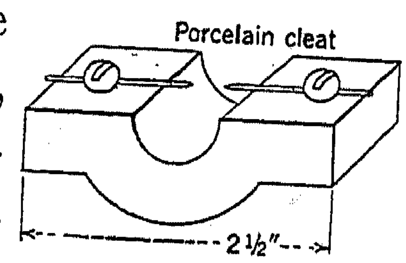

FIG. 3

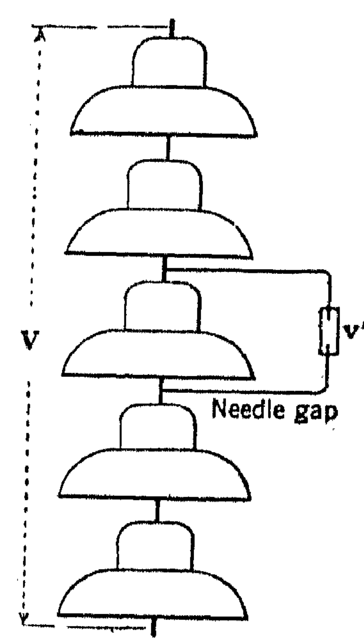

FIG. 4

The units will be numbered from the line towards the grounded end. The line unit being No. 1; the ground unit No. n, or the total number of units. Let v' = spark voltage of needle gap.

$V_1, V_2, V_3, \ldots, V_n$ = total voltage across the string when gap discharges across Nos. 1, 2, 3, etc., respectively.

$v_1, v_2, v_3, \ldots, v_n$ = voltage across units Nos. 1, 2, 3, etc., when total voltage is V_1.

$p_1, p_2, p_3, \ldots, p_n$ = voltage across each unit as a per cent of that across the line unit, No. 1.

$P_1, P_2, P_3, \ldots, P_n$ = per cent of total voltage across each unit.

S = sum of $p_1, p_2, p_3, \ldots, p_n$.

Then the calculations can be arranged as in Table 1.

TABLE I.

Unit No.	v	p	P
1	$v_1 = v'$	$p_1 = 100$	$P_1 = 100\ p_1/S$
2	$v_2 = v'V_1/V_2$	$p_2 = 100\ v_2/v_1 = 100\ V_1/V_2$	$P_2 = 100\ p_2/S$
3	$v_3 = v'V_1/V_3$	$p_3 = 100\ v_3/v_1 = 100\ V_1/V_3$	$P_3 = 100\ p_3/S$
4	$v_4 = v'V_1/V_4$	$p_4 = 100\ v_4/v_1 = 100\ V_1/V_4$	$P_4 = 100\ p_4/S$
n	$v_n = v\ V_1/V_n$	$p_n = 100\ v_n/v_1 = 100\ V_1/V_n$	$P_n = 100\ p_n/S$

It will be noticed that if only percentages are required, it is unnecessary to know v', the gap voltage, and the second column may be omitted.

The errors in the method are due to the capacity of the gap and its leads, and the possible effect of surrounding objects on the spark voltage of the gap.

Results of Tests

Experiments were made on strings of 15 units. The method used was to obtain the distribution on the ungraded units, and then observe the change due to grading in various ways. For experimental purposes the effect of the metal rings was readily obtained by painting the porcelain with a conducting varnish. The string was placed outdoors to avoid the effect of the walls of the building. An iron pipe placed horizontally was used to represent the cross-arm, and the string of insulators was suspended vertically from this, the lower end being about 10 ft. (3 m.) from the ground. A clamp was attached to the string, and held a metal pipe to represent the line wire. The frequency used was 60 cycles.

Fig. 5 gives the results of tests on an ungraded string. Curve No. 1 shows the values of p, the percentage that the voltage on each unit is to that on the line unit. If the distribution of voltage were uniform a horizontal line at 100 per cent would be obtained instead of the drooping curve, No. 1. It will be seen that the lower portion of the curve is nearly horizontal and that the fourth unit from the grounded end has the lowest voltage across it. Curve No. 2 gives the distribution of voltage along the string in per cent of the total voltage. Each successive ordinate is obtained by adding the value of P for that unit to the preceding ordinate. A uniform distribution would give the dotted straight line, No. 3.

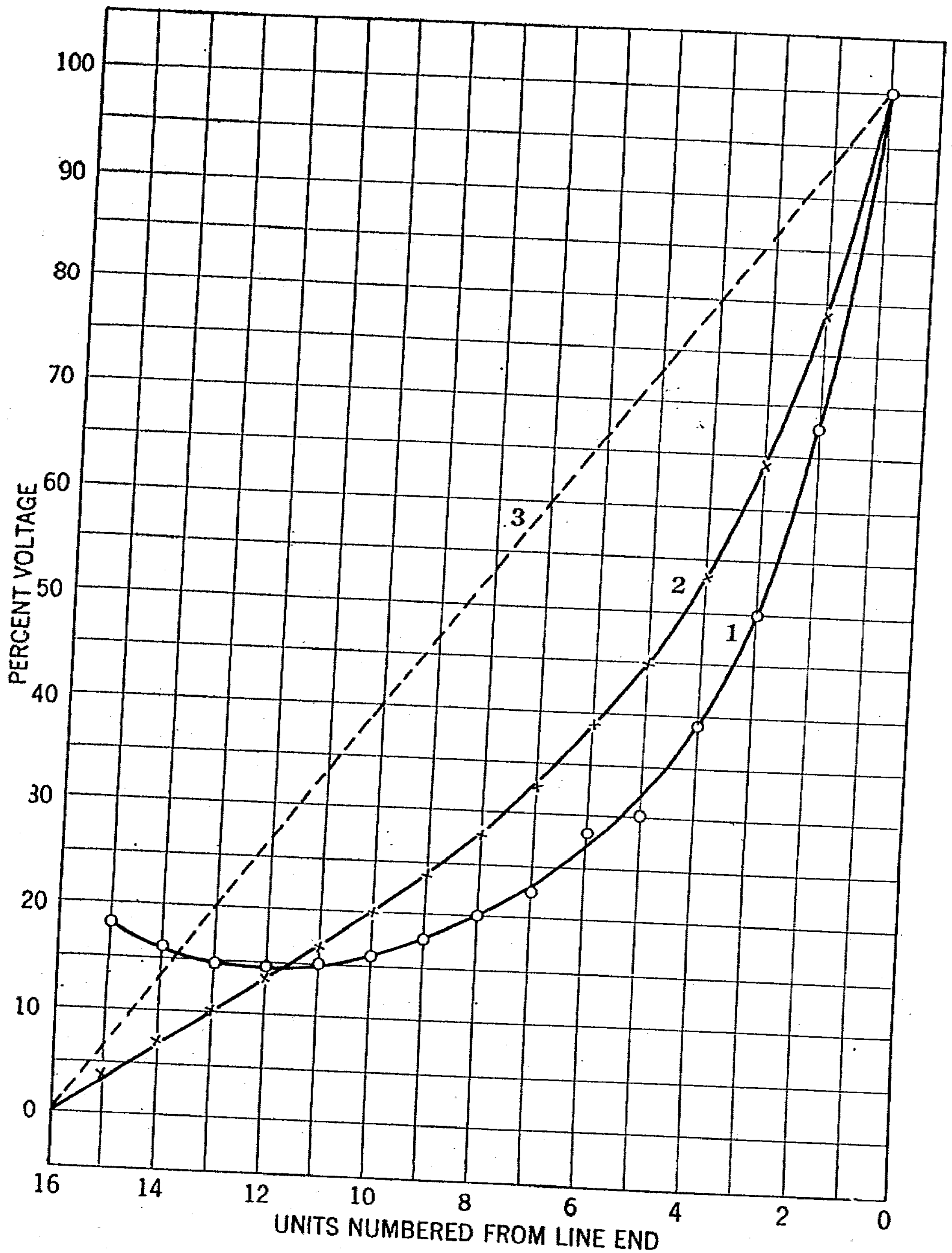

FIG. 5

1—Voltage across each unit in per cent of that across one nearest line
2—Distribution of voltage to ground along string
3—Ideal distribution of voltage to ground along string

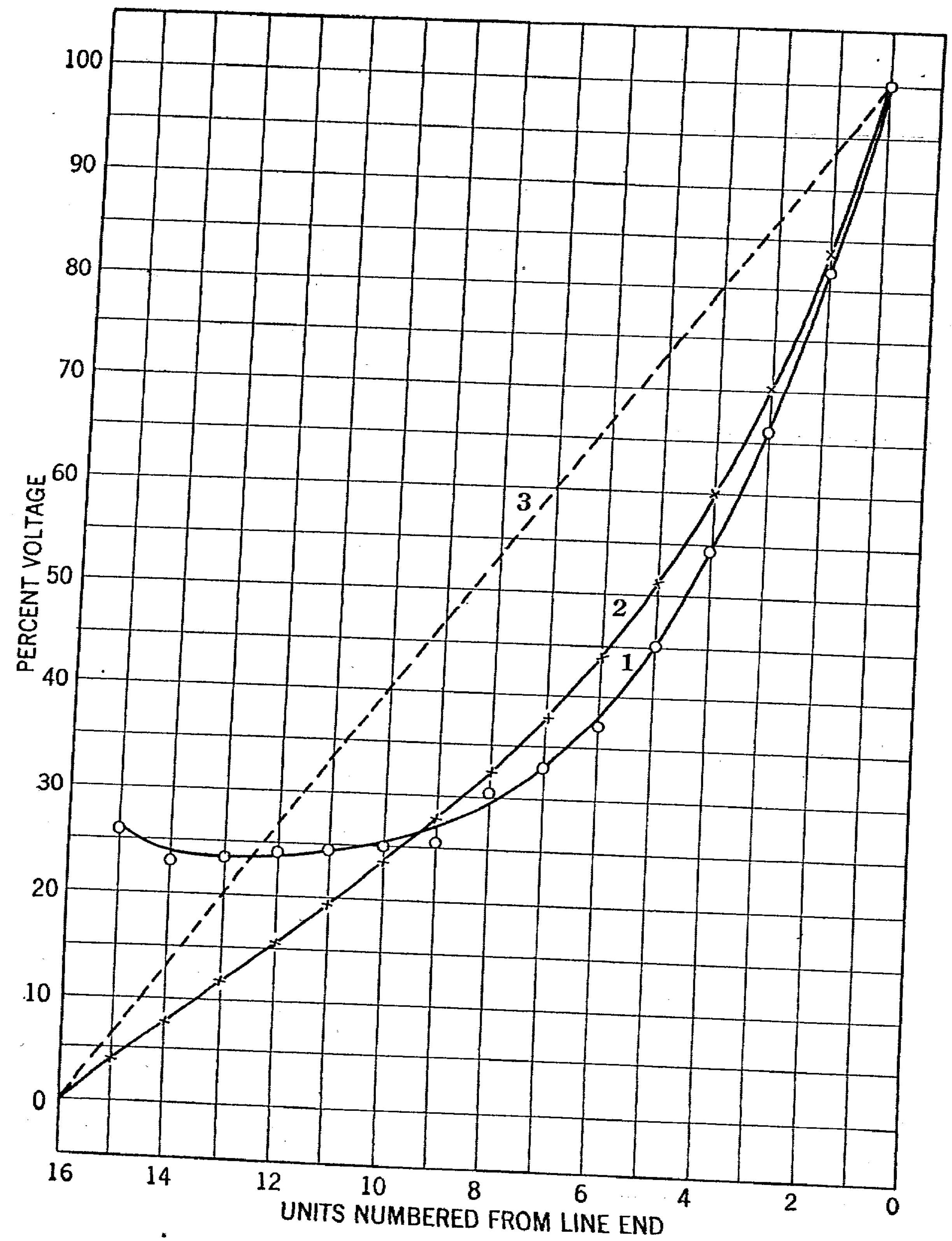

FIG. 6

1—Voltage across each unit in per cent of that across one nearest line
2—Distribution of voltage to ground along string
3—Ideal distribution of voltage to ground along string

Fig. 6 shows similar curves for another type of ungraded unit. In this the internal capacity has a higher ratio to the external capacities. On this account the distribution of voltage is appreciably better, although far from ideal.

Fig. 7 gives the result of grading the type of unit used in the

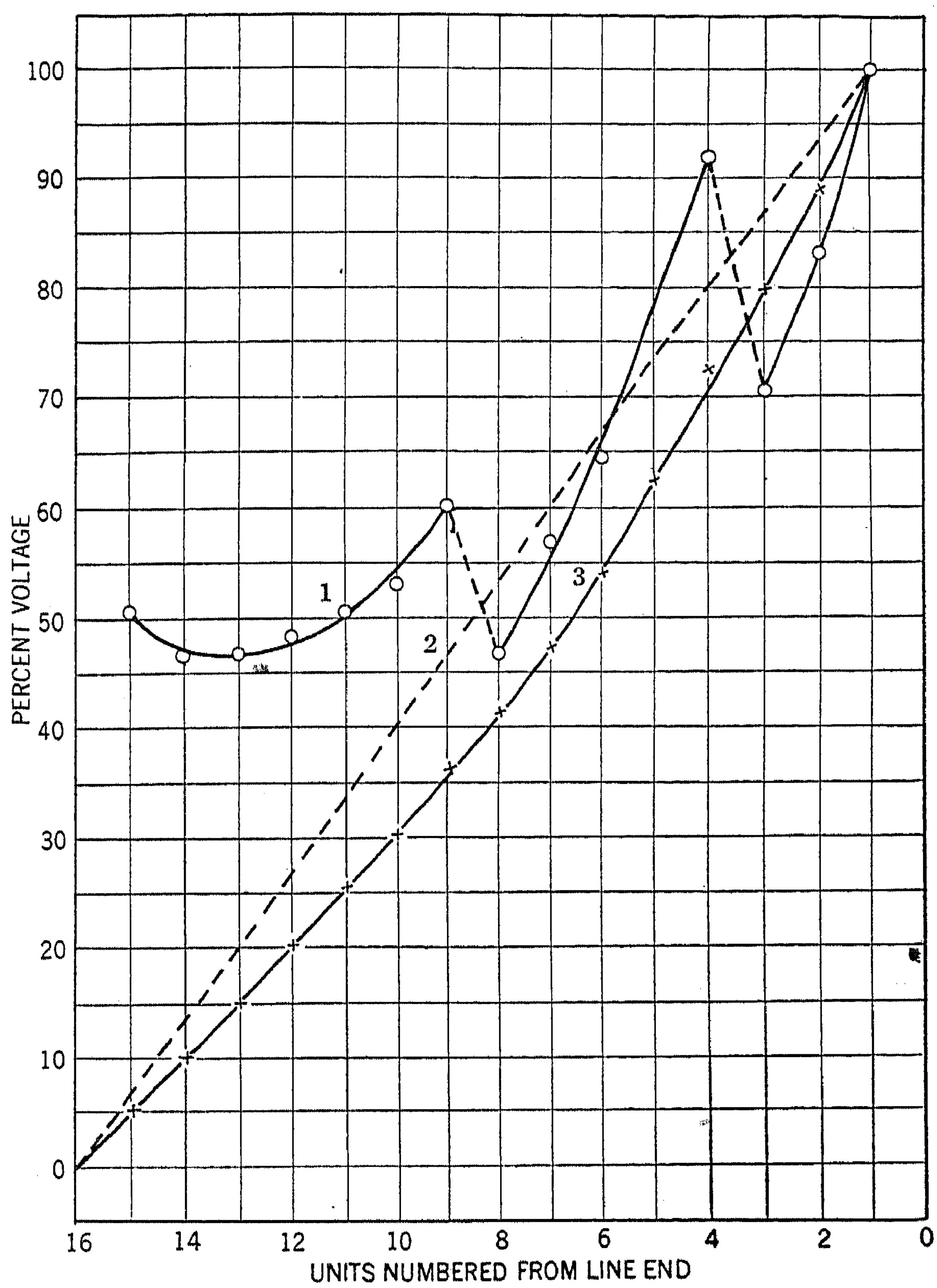

FIG. 7

1—Voltage across each unit in per cent of that across one nearest line
2—Ideal distribution of voltage to ground along string
3—Distribution of voltage to ground along string

tests of Fig. 6. In this case the three units next to the line had the largest conducting disks, and a high internal capacity. The next five units had a somewhat smaller capacity. The last seven units had no coatings. Instead of uniform curves, the result is a broken line formed by joining the curves due to each group. Comparing this with Fig. 6, a great improvement is

evident. Curve 1 is greatly raised toward the horizontal, and curve 3 is nearer curve 2, which represents perfection.

The efficiency of the lowest unit compared to the line unit has been brought from 23.5 per cent up to 46.5 per cent, or nearly doubled. This results in reducing the proportion of the total voltage on the line unit from 16.5 per cent to 11 per cent, a reduction of 27 per cent.

Conclusion

The experiments described in this paper are only preliminary, and much further investigation is desirable. It is felt, however, that the results obtained indicate the value of this method of grading where the voltage is such as to require the use of many units.

DISCUSSION ON "MEGGER AND OTHER TESTS ON SUSPENSION INSULATORS" (HUNT), "EXPERIENCES IN TESTING PORCELAIN INSULATORS" (CREIGHTON), "A NEW METHOD OF GRADING SUSPENSION INSULATORS" (MARVIN), CLEVELAND, OHIO, JUNE 28, 1916.

F. W. Peek, Jr.: I would like to say a word of warning on the danger of misinterpreting data, especially in regard to insulator testing. I have noticed that there is a great tendency to do this. For instance: The conclusion that a certain specified test is better than another test, and selects the good insulators from the bad, because a greater percentage of insulators are destroyed by that test, may be erroneous. It is, perhaps, best to take a practical example by way of illustration.

It is bad practise to test any insulation up to within a few per cent of the breakdown voltage, as damage always results. The strength of a given thickness of any given kind of insulation *in good condition* will vary from the average 5 to 10 per cent plus or minus on account of structural differences, etc. For instance, the strength of a given thickness of porcelain *in good condition* which averages 100 kv. may vary, for different pieces, from 90 to 110 kv. If this porcelain is arranged in insulators with a flash-over voltage of 100 kv. 60-cycle, and tested at 60 cycles until flash-over takes place, the failure will be about 50 per cent. This follows from the fact that the strength of about 50 per cent of this insulation is below 100 kv. The high-frequency flash-over voltage is higher than the 60-cycle flash-over voltage.* Thus, if high frequency is employed so that it is possible to apply a higher voltage, or 105 kv., before arc-over occurs, the percentage failure will be about 75 per cent. In the above test a greater loss will occur on *good* porcelain at high frequency than at 60 cycles. The action is not selective, much porcelain is destroyed, and that porcelain which passes will be damaged and much worse than if the tests were not made at all. The conclusion might be reached here that better insulators are being obtained because a greater number are being broken down. This is far from the actual fact for this particular case. A few bad pieces are being broken down, it is true, but much of the good porcelain is also being destroyed, and all of it is being damaged. This is an extreme case and the peculiar conditions obtain because the puncture voltage is so near the arc-over voltage, and an arc-over voltage test is specified. It is a bad test for this particular design.

Naturally, this does not mean that this insulation should not be tested. It means that it should be tested at a voltage lower than the minimum voltage at which good porcelain of this particular thickness and shape will be damaged or broken down. Fortunately, the condition which exists for the above

* "High-Frequency" Damped Oscillations. See F. W. Peek, Jr., "The Effect of Transient Voltages on Dielectrics," A. I. E. E., TRANS. Vol. XXXIV, 1915, p. 1857.

insulator does not obtain in most insulator tests, as the designs are usually such that the puncture voltages are much higher than the flash-over voltages. This should, in general, be the case, when the high-frequency test becomes useful.

The high-frequency test has very important uses and also limitations. Its most important use is to locate cracks and flaws in insulators. It will not detect moisture as readily as the 60-cycle test.

All of the tests in general use are devised for locating faults after they occur; they are successfully used for this purpose. There is much need of tests for anticipating deterioration at the factory in order to eliminate the great expense of testing and changing insulators after a year or so of service. The so-called deterioration of porcelain is due to two main causes—gradual absorption of moisture by porus porcelain, and gradual cracking due to mechanical stress of poor design, cement, firing, etc. Failures often result only after several years of service. There is no volatge test in use at present that will anticipate in the factory conditions which will later cause failure on the lines by absorption and cracking. Such conditions may be anticipated, not by high voltage, but by absorption tests, and such mechanical tests as expansion and contraction, etc.

E. E. F. Creighton: I am going to agree immediately with Mr. Peek on one point and get it out of the way, and that is that there is no electrical test known today that will eliminate all defective porcelain. Porcelains are porous from about 1 per cent down to perhaps 0.005 of 1 per cent, as far as we have been able to measure. We have not yet connected up the relation between the test and the porosity, but we have this one very useful, practical result, that the test with the high-frequency oscillator in the factory, where the porcelains come directly from the furnace, and where the oscillator is specially fitted for the test, eliminates on the average about 8 per cent more porcelains than the 60-cycle test.

The man who wants to use the insulators is interested in getting the very last bad one out. The oscillator does not, apparently, take all the bad ones out. There are some of very small porosity which may or may not develop later on into poor insulators by absorbing moisture from the cement. But, at any rate, we can say that the application of the high frequency from the oscillator is one step better than the 60-cycle test. We hope to find some suitable way before long of eliminating the bad insulators immediately after manufacture.

In regard to the other point, the relation of the 60-cycle test to the high-frequency test, as regards the damage possible to insulators. Taking up the illustration that Mr. Peek gave, of an insulator which is just about to fail on the test voltage. In the case of the 60-cycle test voltage, the flash-over takes place in the insulator at about 100 kilovolts, the average is in that neighborhood. If the strength of the insulator is a little bit

below that, the insulator will fail. If the puncture voltage of the insulator is above, the insulator will probably be damaged by the test. The 60-cycle test will leave a certain number of defective insulators to be accepted and placed on the line, when the puncture voltage is only a small percentage above the flash-over voltage.

Turning to the oscillator test, on that same insulator the oscillator test will subject it to 120 kilovolts or 130 kilovolts, and there, again, there will be some insulators which will be ready to break down at that potential, which will not quite break down in the time of application, and they will go through as defective insulators, but after they have gone through as defective insulators, they still have a factor of 30 per cent above their flash-over value, and therefore, from the operating man's standpoint, they are a better insulator than those which barely pass the flash-over test at 60 cycles.

I think that is the answer to the criticism of applying voltages which might damage the insulators. The solution of the problem is to make the insulator so perfect that it will have the proper design and will be made of the proper porcelain to have a factor of safety over, say, the 130 kilovolts of applied potential.

As a result of a comparison between the two tests, the 60-cycle and the high-frequency test, in our factory we have given up entirely the 60-cycle test and replaced it with the high-frequency test. Some of the more recent results, especially those obtained by Mr. Hunt, may make it expedient to apply both the 60-cycle and the high-frequency test to the finished insulators.

Presented at a meeting of the Schenectady Section of the American Institute of Electrical Engineers, Schenectady, N. Y., May 4, 1916.

ILLUMINATION OF THE PANAMA-PACIFIC INTERNATIONAL EXPOSITION

BY W. D'A. RYAN

ABSTRACT OF PAPER

In this paper the author, who was Chief of Illumination for the Panama-Pacific International Exposition in San Francisco, describes the system of lighting adopted for the Exposition, which was generally conceded to have initiated a new era in the art of illumination. From a narrow engineering point of view the lighting would have been regarded as inefficient, but the object striven for was to suppress high intrinsic brilliancy, while bringing out the architectural beauties of the Exposition structures in the most effective manner, bathed in a harmony of color. Many beautiful effects were obtained by the various installations which are described, and one of the most original features was the successful effort to preserve the curvature and detail in relief by the use of lights of different strengths and colors thrown from different or opposite directions upon the same object.

THE illumination of the Panama-Pacific International Exposition was finally classed by the International Jury of Awards as a "decorative art", largely because it appealed to the imagination and feelings of the masses, and carried a message much the same as painting or music, as demonstrated by the happy enticing effect of the heraldic banners on the Avenue of Progress, the deep mystery in the Court of Abundance, the grandeur and uplifting effect of the great candle-fountains in the Court of the Universe, the quiet peaceful illumination in the Court of the Four Seasons and on the Palace of Fine Arts, the Alladin dreams and fairy-like suggestions of the illuminated towers, flags, reflections and other features which made up the lighting as viewed from the South Gardens.

In this connection I wish to quote Edwin Markham's impressions gained on try-out night, February 15, 1915:

"I have tonight seen the greatest revelation of beauty that was ever seen on the earth. I may say this, meaning it literally and with full regard for all that is known of ancient art and architecture, and all that the modern world has heretofore seen of

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NOTE: The colored illustrations for this paper were supplied through the courtesy of the Schenectady Section of the American Institute of Electrical Engineers.

glory and grandeur. I have seen beauty that will give the world new standards of art and a joy in loveliness never before reached. This is what I have seen—the courts and buildings of the Panama-Pacific Exposition illuminated at night."

The illumination of the Exposition was based on developments of the science of lighting, and represents results of personal experience in this field extending over a period of twenty years.

The lighting for the Exposition was completely designed in the latter part of 1912 and every feature was carefully calculated, as there was practically no opportunity for trial, owing to the radical nature of the scheme and scope. The buildings of previous expositions had in the main been used as a background upon which to display lamps. The art of incandescent outlining, notably the beautiful effects obtained at the Pan-American Exposition at Buffalo, could probably not be improved upon, and furthermore, this form of lighting had been extended to amusement parks throughout the world and had become commonplace. Its principal disadvantages were the diminution of artistic effectiveness at close range, similarity in effects from different view-points, the suppression or complete obliteration of architectural features, and the economic necessity of extensive untreated surfaces. Furthermore, the glare from so many exposed sources when assembled on white or light-colored buildings, caused severe eye strain.

The lighting scheme and scope of the Panama-Pacific International Exposition called for a radical departure from previous practise. Incandescent outlining on the main group of palaces was avoided, and screened or masked flood and relief lighting to produce the third dimension or depth, substituted, and great care was exercised to preserve the architectural features and color, with proper relative intensities. For the first time at an international exposition, the illuminating sources, whether arcs, incandescent or gas, lost their identity as such. While a uniform system was maintained throughout, each court possessed its individual characteristics with radical differences, and at the same time the transition from one effect to another was harmonious, even to the extent of an intermediate step or carnival effect on the Avenue of Progress connecting the Zone and the main group of palaces.

During the pre-exposition period, there were many who maintained that the general public would not be attracted except by the glare of exposed brilliant sources. The lighting of the Ex-

position, however, immediately disproved this theory and a strong psychological appeal was made by the highly artistic lighting effects.

During the period elapsing between the Louisiana Purchase Exposition and the Panama-Pacific International Exposition, wonderful advances had been made in the efficiencies of all types of lighting units. This made it possible to illuminate in the main group of buildings, approximately 8,000,000 sq. ft. (743,200 sq. m.) of horizontal and vertical surfaces to an illumination ranging from 1/10 to 1/4 of a foot-candle in the incidental gardens and roadways, from 1/4 to 3 foot-candles in the building facades and adjacent lawns and gardens, and from 5 to 15 foot-candles on the towers, flags and sculptural groups. The lighting load on the main group of buildings, including the window lighting and the scintillator, was approximately 5000 kw. The total connected load for all purposes, including Zone, Foreign and State sections and exhibitors, for light and power, was 13,954 kw., with a maximum peak of 8200 kw. and an average peak of 7880 kw. During the Exposition period of approximately ten months, a total of 16,057,790 kw-hr. was purchased from the Pacific Gas and Electric Company. Of this amount, 5,582,906 kw-hr. were sold to exhibitors and concessionaires, the remaining 10,474,884 kw-hr. being used by the Exposition.

While the lighting of the Exposition was primarily electric, all modern sources of intrinsic merit were used, and a number of excellent gas features were introduced. About four miles of streets in the Foreign and State sections were illuminated with Penn globe high-pressure gas "arcs," in 20-in. (508-mm.) opal globes mounted with their centers about 16 ft. (4.9 m.) above the roadways on ornamental poles spaced approximately 100 ft. (30.5 m.) apart, staggered. The same type of lamp was used for emergency lighting on the kiosks throughout the grounds. Five-mantle Humphrey gas "arcs" enclosed with ornamental lanterns were used in pairs on the standards in the Zone (amusement section) and the same type of lamp, of smaller sizes, furnished emergency lighting at the gates and important exits from the main group of buildings. Gas flambeaux were introduced in the effects in the Court of Abundance and the North Approach. The total gas flow for the purposes mentioned was approximately 15,000 cu. ft. (425 cu. m.) per hour. The average amount of gas consumed daily at the Exposition for all purposes was 486,550 cu. ft. (13,780 cu. m.). The total amount purchased by the Exposition Company during the

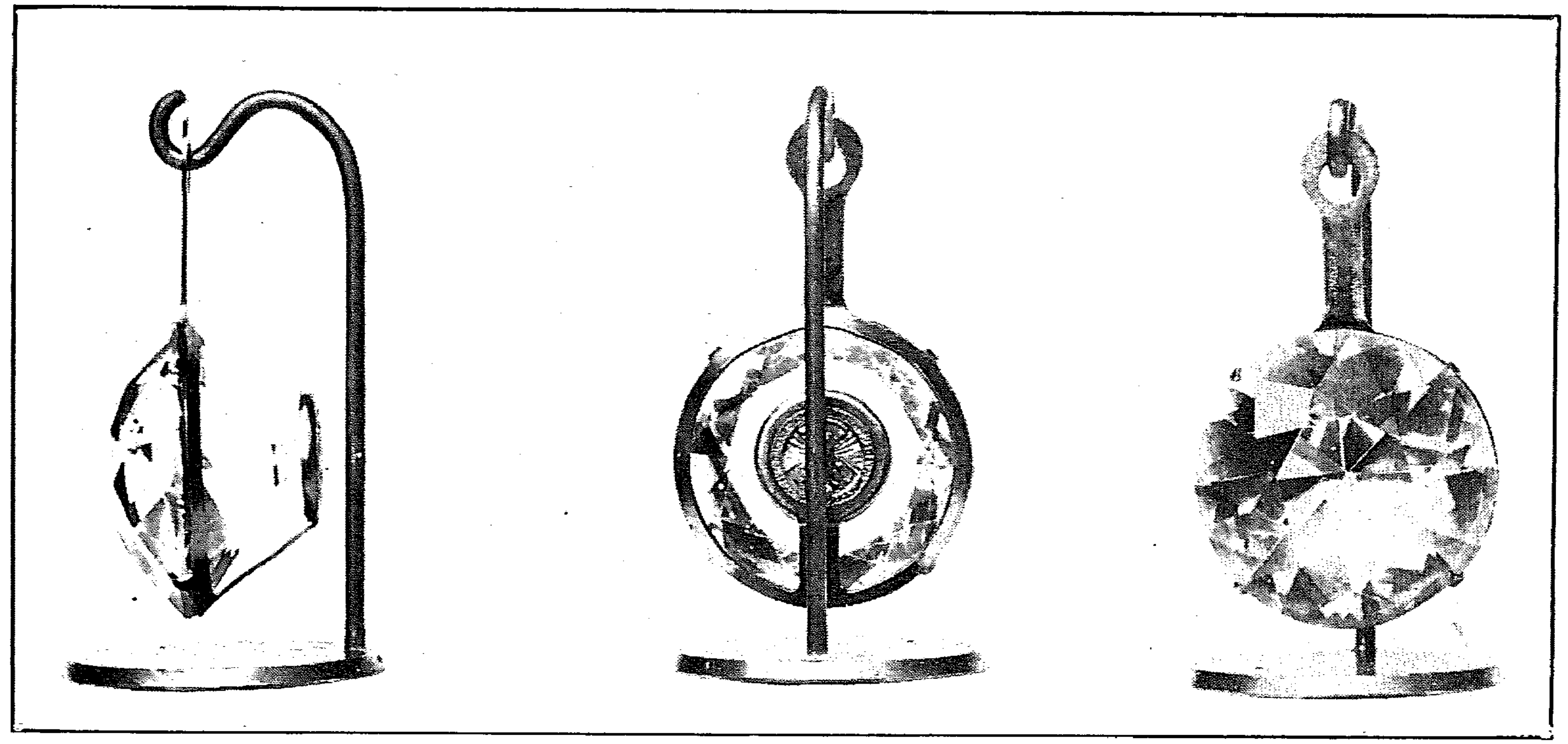
Exposition period was 121,913,500 cu. ft. (3,452,590 cu. m). Of this amount only 25,101,496, cu. ft. (710,874 cu. m.) was used by the Exposition Company, the remainder being sold to exhibitors and concessionaires.

In order to obtain a harmonious illumination scheme, it was necessary to visualize the lighting as a whole, and to establish illumination and color values for every part of the Exposition before definite specifications for lighting equipment could be made. The preliminary tests and calculations on lighting units that had been selected for use at the Exposition were made at the Illuminating Engineering Laboratory. The work of calculation was greatly shortened and simplified by the use of various graphical charts, one of which, an illumination chart, is described by Mr. Frank A. Benford, Jr., in the *Transactions* of the Illuminating Engineering Society*. The lighting units were all new developments, in many cases used in new ways. This necessitated a vast amount of preliminary investigation which usually took the form of calculations of the illumination on the grounds, facades and towers. From these calculated values it was possible to determine if the selected lighting units were of the right size and were properly arranged on the preliminary plans. As soon as any particular phase of the lighting was fully decided upon, the illumination and luminous flux values were calculated in all their minute details, so that long before the Exposition opened there were on hand complete sets of illumination diagrams for all the various courts, buildings and towers. Some of these diagrams are illustrated by Figs. 7, 8, 16, 20 and 23, which are referred to later.

The principal features of the lighting are described under their respective headings and illustrated by the accompanying plates.

Luminous Effects in Tower Illumination. This illumination consisted in flood-lighting the towers with a white rising light which created shadows. The shadows were in turn illuminated by concealed colored light on the various stages, thereby producing detail in shadow. This combination gave the structures a luminous effect never before obtained. These towers further illustrated the preservation of depth, or the third dimension in light, which feature predominated throughout the Exposition. The Tower of Jewels was flood-lighted by batteries of arc projectors located on the roofs of the main group of palaces, the

*Vol. VII, page 695, 1912.



[RYAN]

FIG. 1—NOVAGEMS MOUNTED IN BRASS HOLDER

Fig. 2—Breaking Up of Incident Light Passing Through Novagem Jewels

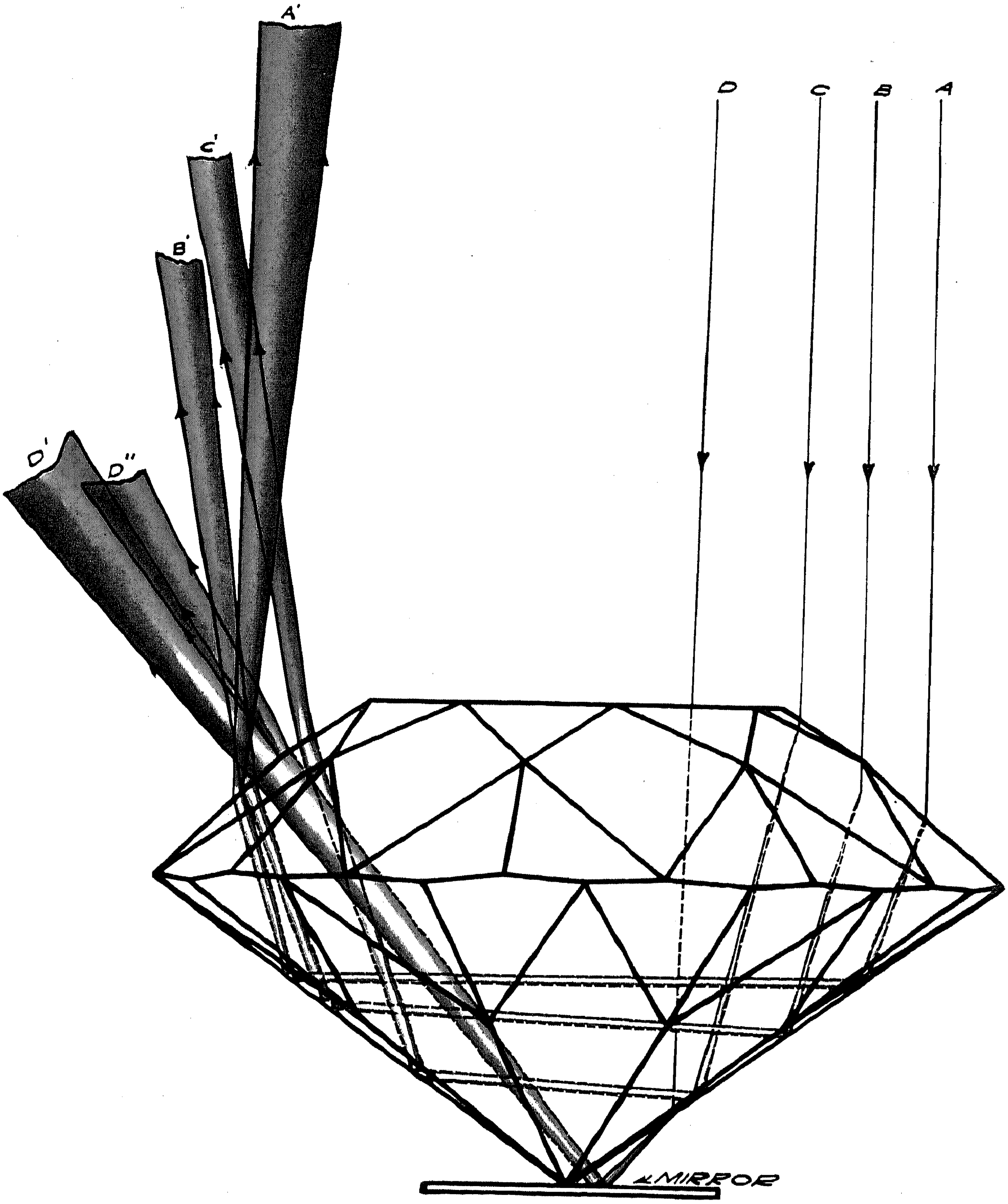

A'
C'
B'
D'
D''
D
C
B
A
MIRROR

PLATE XIX-XX.
A. I. E. E.
VOL. XXXV, 1916.

Fig 3—Spectra Produced by Single Beam of Light

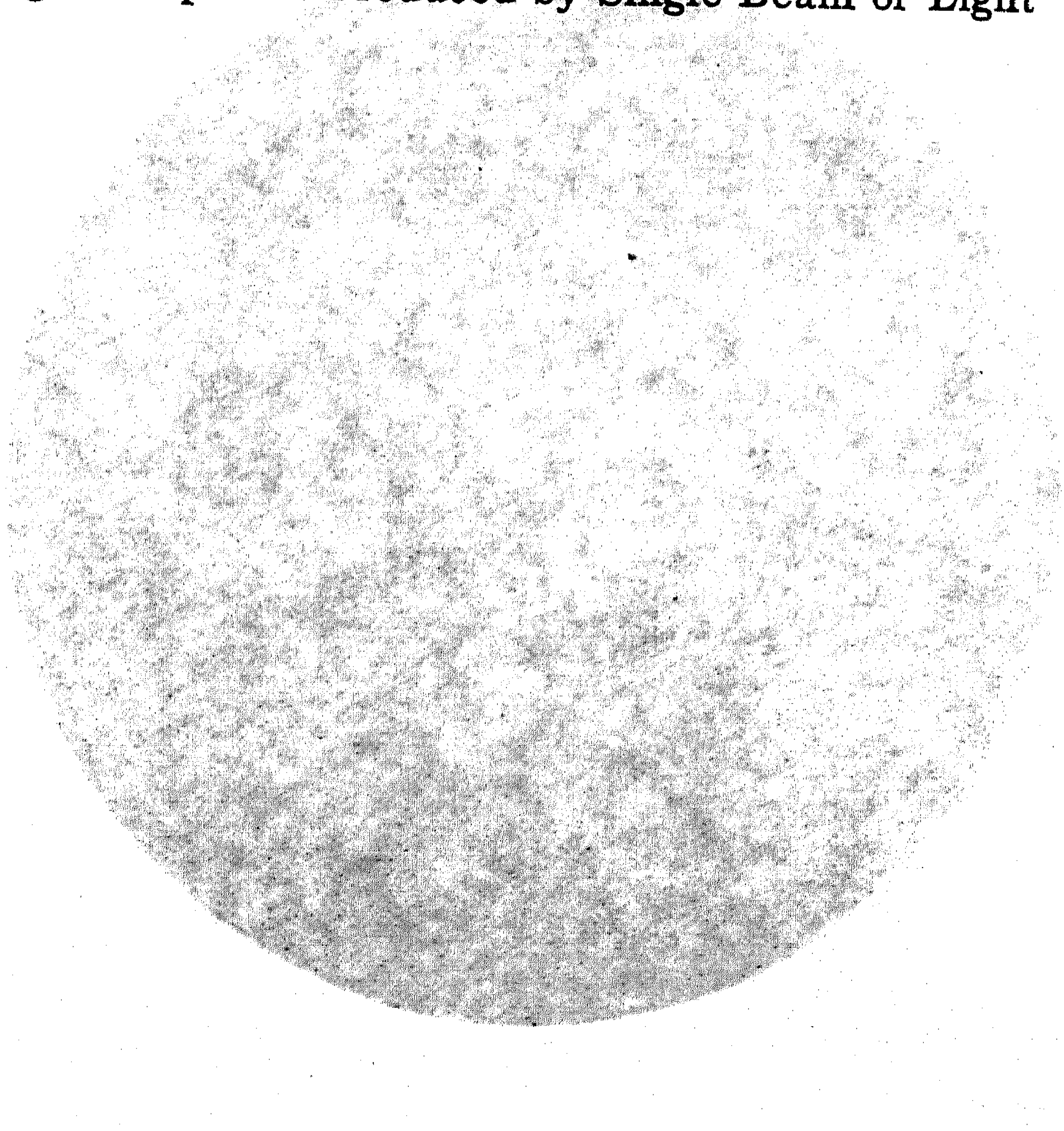
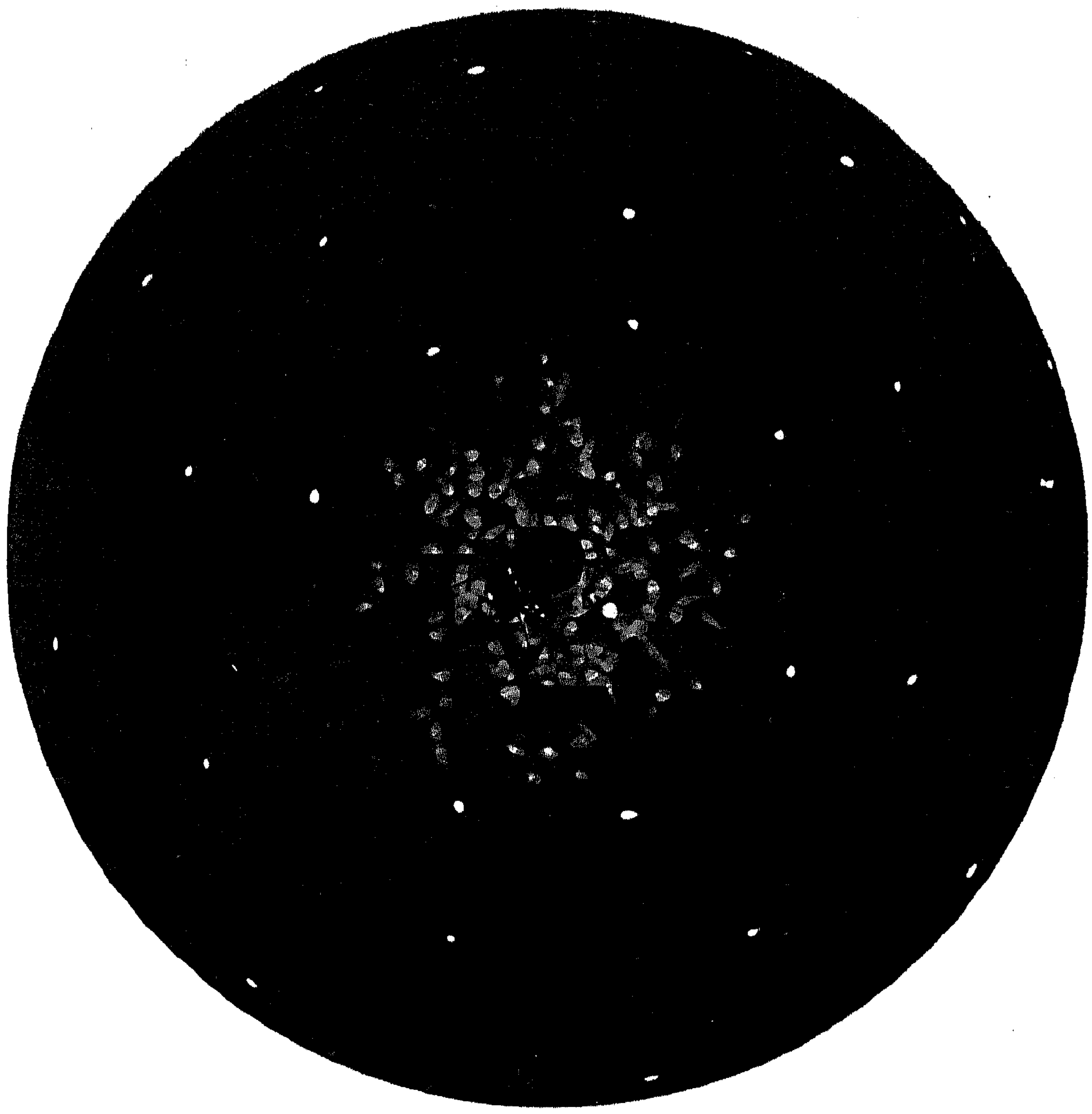
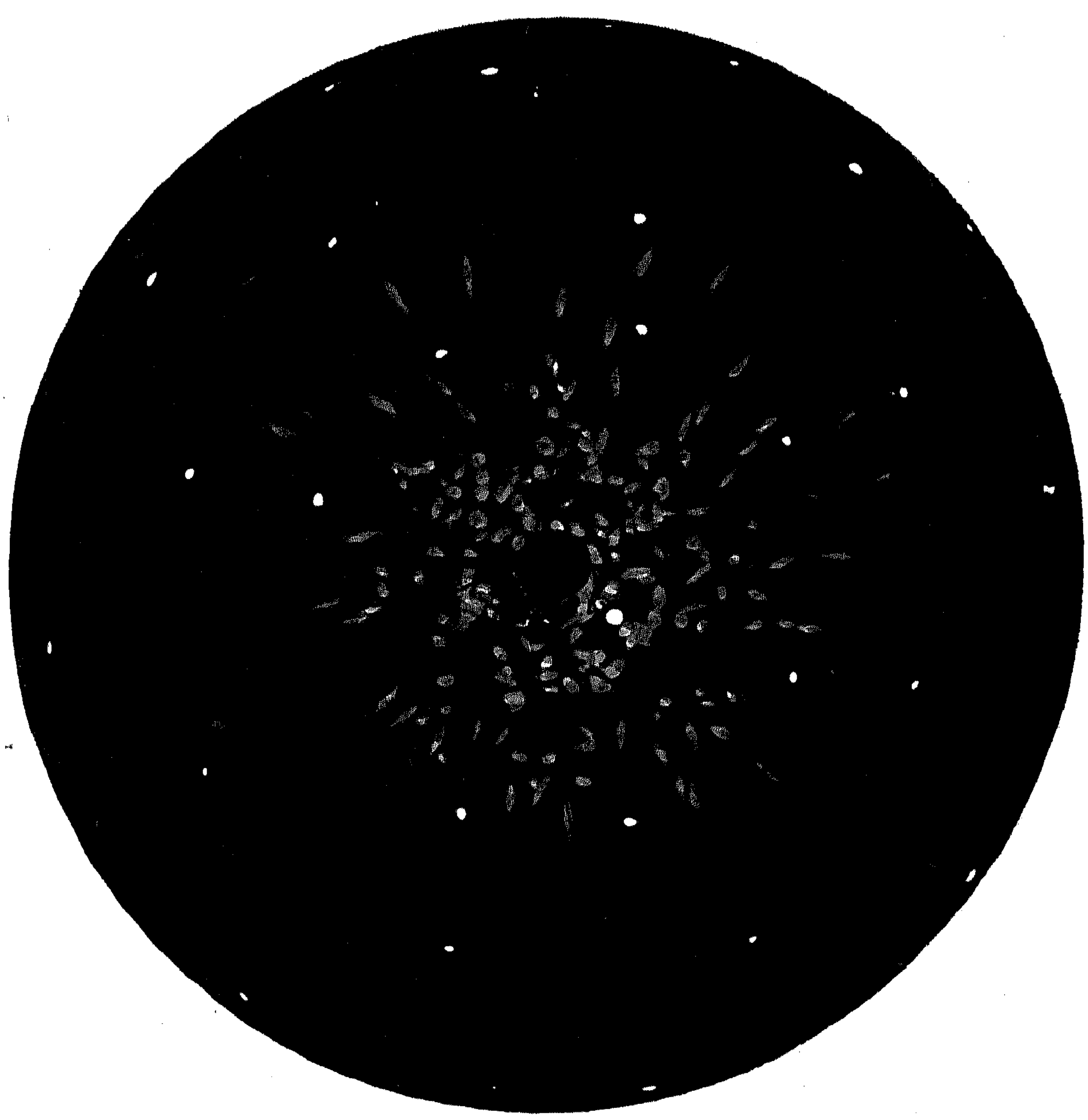


Fig. 3A—Increased Spectra Due to Use of Mirror





South Garden pavilions and the Scott Street entrance gate. In order to obtain the proper gradation of light with an economic distribution, it was necessary to equip the majority of the projectors with properly designed diverging doors. A complete set of color screens at each projector enabled the changing of the color tone of the tower on very short notice. The base section was necessarily carried in the same relative illumination as the building facades. Above this section there was a rising illumination to approximately 20 foot-candles on the top ball. The average value for all levels was 10 foot-candles. The shadows cast by the rising searchlight beams were illuminated by rose red relief lighting. At the top level there were four 30-in. (762-mm.) arc projectors equipped with changeable color screens for spectacular and heightening effects. The twin Italian towers at the entrances to the Courts of Palms and Flowers were lighted in a similar way.

"Novagem" Jewels. "Novagem" jewels are scientifically cut glass of high index of refraction, made to imitate diamonds, rubies, sapphires, emeralds, etc. Each was mounted in a suspension carrying a mirror at the apex of the stone, which increased the spectra approximately forty per cent. These jewels were used to carry architectural lines in addition to being massed on shields and other points. They were mounted in such a way that they were kept in motion by the wind, thereby adding action to the effect when illuminated with projected light, which, especially in the white stones, produced all the colors of the spectrum with unusual purity. 102,000 47-mm. diameter jewels were used on the Tower of Jewels, and about 4000, in sizes from 21 to 47 mm., were hung on the star heads of the seraphic figures in the Court of the Universe. Fig. 1 shows one of the novagems mounted in the brass holder. Fig. 2 illustrates the breaking up of the incident light passing through one of the 47-mm. stones. Fig. 3 is a reproduced from a photograph of the spectra produced by a single beam projected normal to the plane of the table. Fig. 3A shows the increased spectra due to the use of the mirror.

The following table gives the indices of refraction, specific gravity and weight of the 47-mm. stones:

Indices		Specific gravity	Weight, 47-mm.
Yellow	1.669	3.925	0.235 lb. avoir.
White	1.616	3.589	0.221 lb. "
Pink	1.618	3.595	0.216 lb. "
Ruby	1.618	3.87	0.237 lb. "
Amethyst	1.616	3.55	0.234 lb. "

The Electric-Steam Color Scintillator. The scintillator consisted of combining searchlights in systematic drill in colored and white beams with smoke and steam, so as to produce spectacular

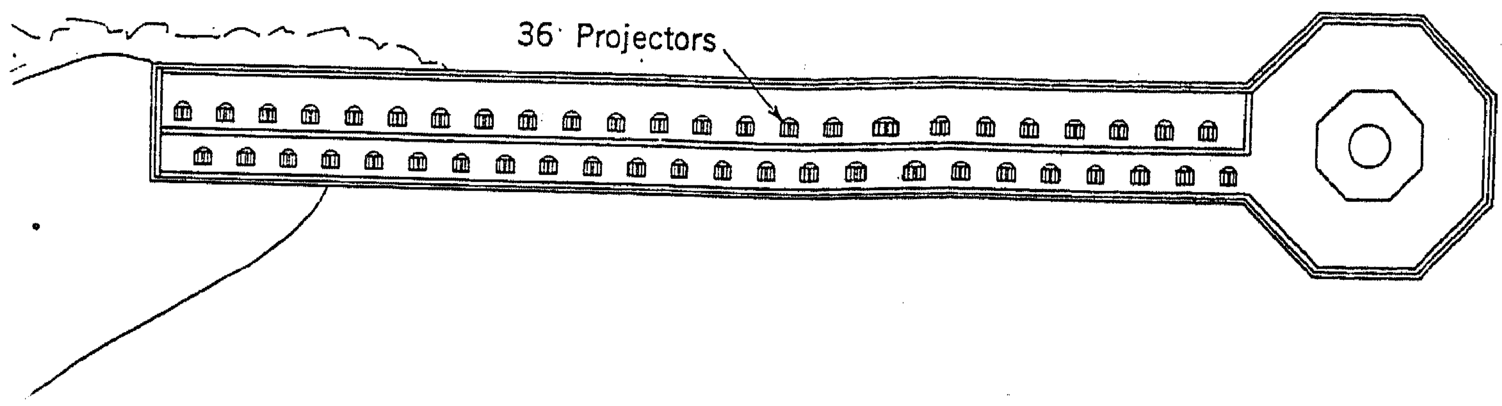


FIG 4—ELECTRIC COLOR SCINTILLATOR

effects or fireless fireworks, both aerial and on the ground, possessing artistic color combinations and blendings impossible with ordinary fireworks. This was further enhanced by the running of a large express locomotive at high speed under brake so as to

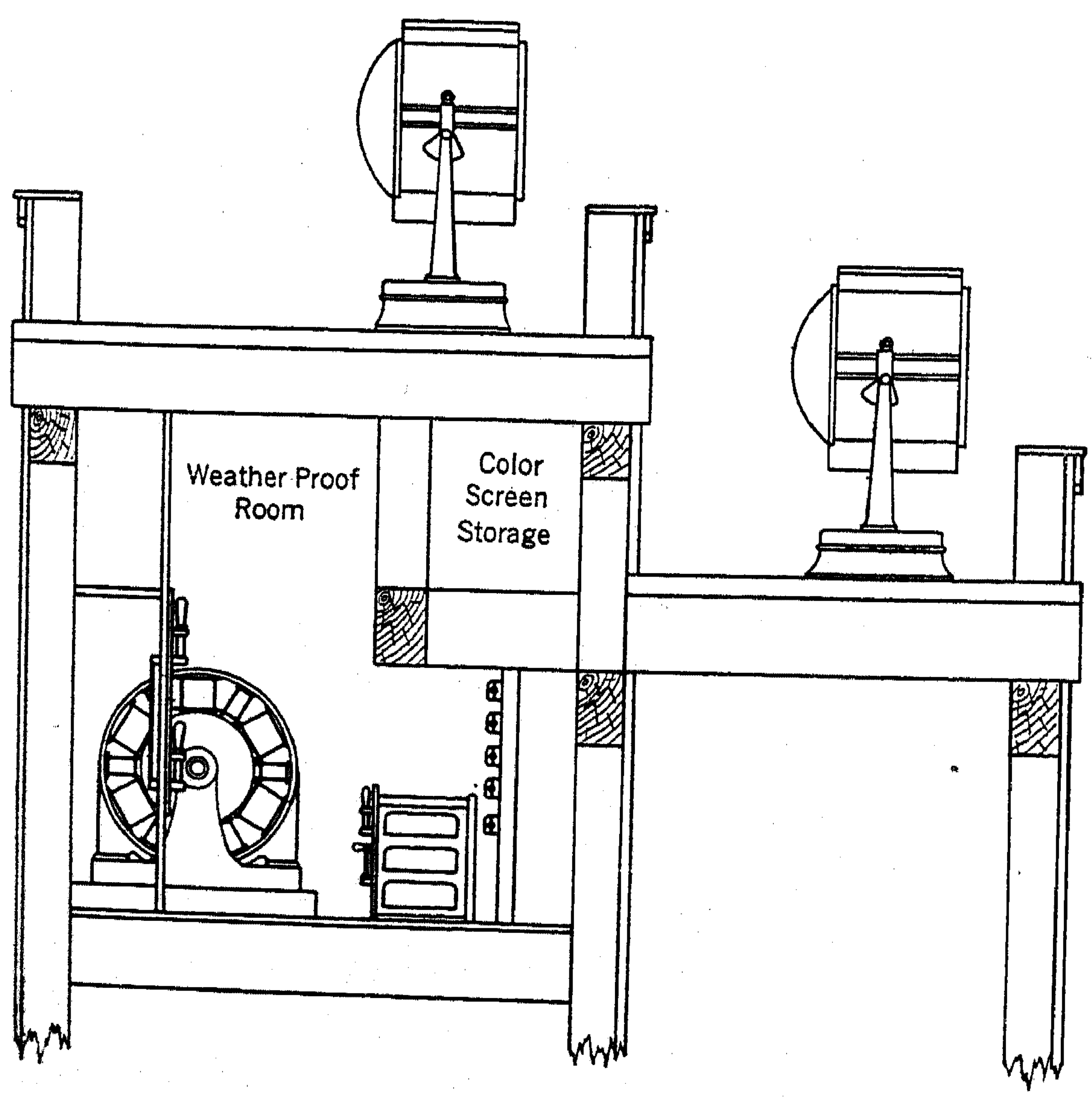


FIG. 5 — CROSS SECTION OF ELECTRIC COLOR SCINTILLATOR

produce large volumes of smoke and steam which were illuminated in color. Other steam effects were in the form of fans, plumes, wheels, fighting serpents, etc. This battery was composed of 48 36-in. (914-mm.) hand-controlled arc projectors. They

were operated at nominal 110 volts, 110 amperes, and with the resistance consumed a total of 581 kw. The beam candle power of each was approximately 55,000,000, or an aggregate of 2,640,-000,000 for the battery. With the equipment of each projector was a set of seven colored gelatine screens, treated with spar varnish and turpentine as a protection against moisture.

These searchlights were located on the double deck pier on the north breakwater of the yacht harbor (Fig. 4), which was constructed as shown by the cross-section drawing (Fig. 5). Part of the space below the upper deck was used for housing the color screens, resistance boxes and distribution system, as well as a 250-kw. motor-generator set (see photographs) which supplied part of the power for the projectors. The remainder of the power necessary was taken from a 1000-kw. set located in the Palace of Liberal Arts.

The locomotive, steam apparatus and fireworks mortars were located on the south breakwater of the yacht harbor (Fig. 6).

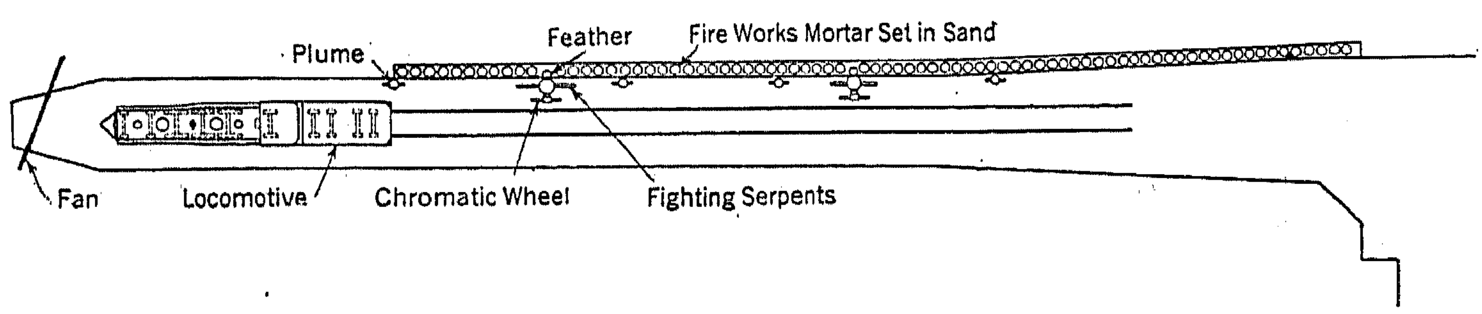


FIG. 6—STEAM SECTION OF ELECTRIC STEAM COLOR SCINTILLATOR

In addition to supplying the various steam effects such as plumes, chromatic wheels, fairy feathers, etc., this locomotive, which was a modern Southern Pacific oil-burning passenger type, was blocked up and locked so that the wheels could be driven at a speed of 60 miles (97 km.) per hour under brake. Thus great volumes of steam and smoke were produced, which, when illiminated with various colors, created a wonderful spectacle.

Banner and Cartouche Lighting Standards. The banner standards consisted primarily of anywhere from two to nine ornamental luminous arcs mounted on 25- to 55-ft. (17- to 7.6-m.) shafts, the lamps being screened by banners in such a way that they flood-lighted the buildings, lawns, trees and shrubbery, and at the same time, the direct source was not visible in the main vistas. These banners, which formed decorations by day and beautiful spots of color by night, were hung so that they moved in the wind, adding action to the effect. At the same time, they were weighted and guided in such a manner that they did not

expose the source or become self-destructive by whipping. As a matter of further interest, the history of California and the Pacific ocean was written in the designs on the three-, five- and seven-light banners, by the use of the heraldic shields of the early explorers and pioneers. The banner standards were used

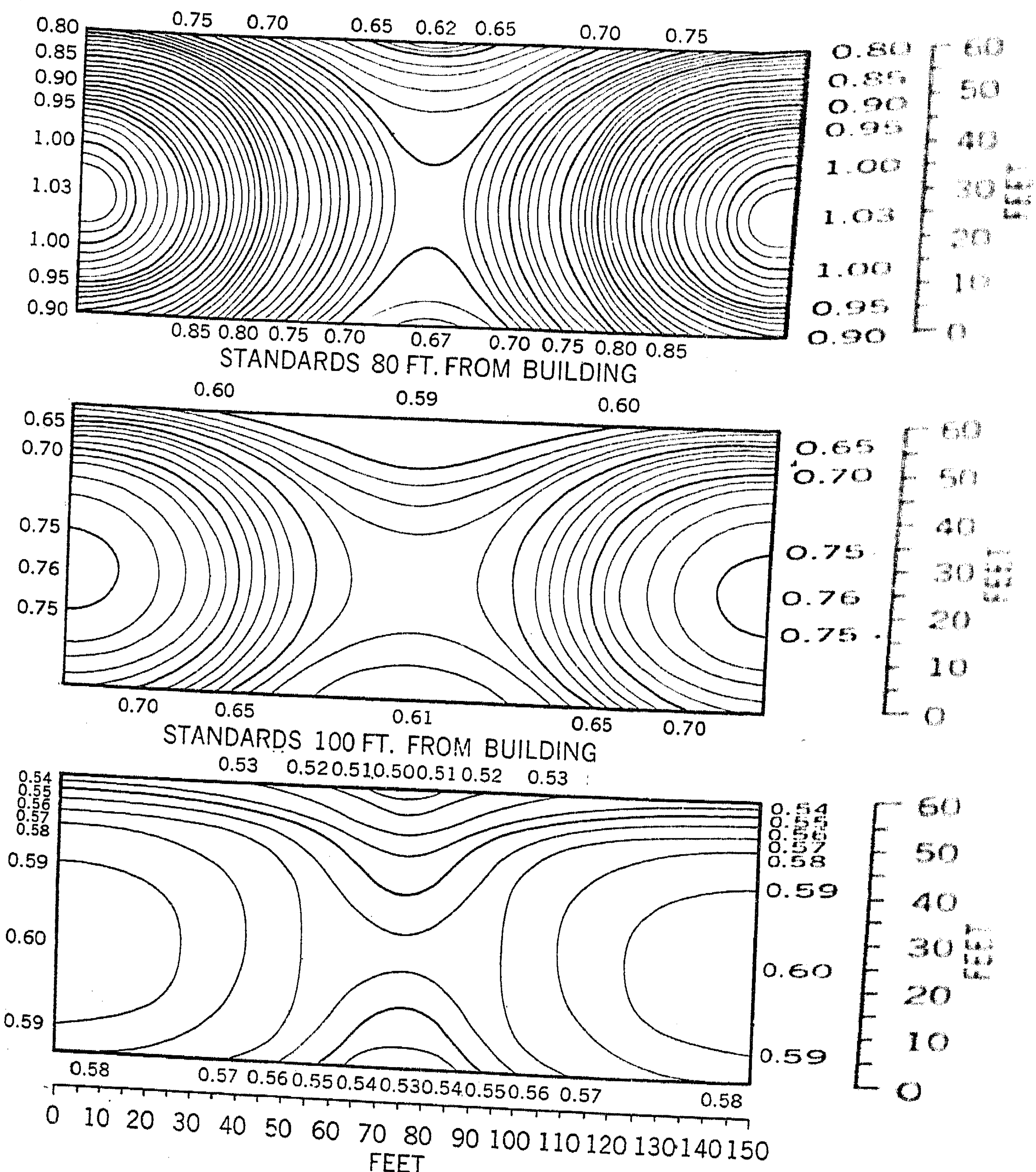


FIG. 7—ILLUMINATION ON EXTERIOR OF BUILDINGS—FIVE LIGHT STANDARDS

Light reflected from banners adds 20 per cent to the above values

for flood-lighting the Court of the Four Seasons, the Palace of Horticulture, Festival Hall, all palaces fronting on the Avenue of Progress, and the central group on the Avenue of Palms.

The three isolux diagrams shown in Fig. 7 give the foot-candle values obtained in preliminary calculations for the illu-

mination of the exterior facades of the main group and furnished a basis for estimating the number of lamps required for general surface illumination. Fig. 8 shows a preliminary curve of foot-candle values calculated for the building facades within the Court of the Four Seasons. The photometric test values taken under operating conditions checked very closely with these original calculated values.

The cartouche standard was of the same order as the banner standards, except that painted translucent fabric was used in place of canvas, which was not free to move, being held rigidly in the cartouche. In addition to screening the direct light from the people, it created pleasing spots of color in contrast with the

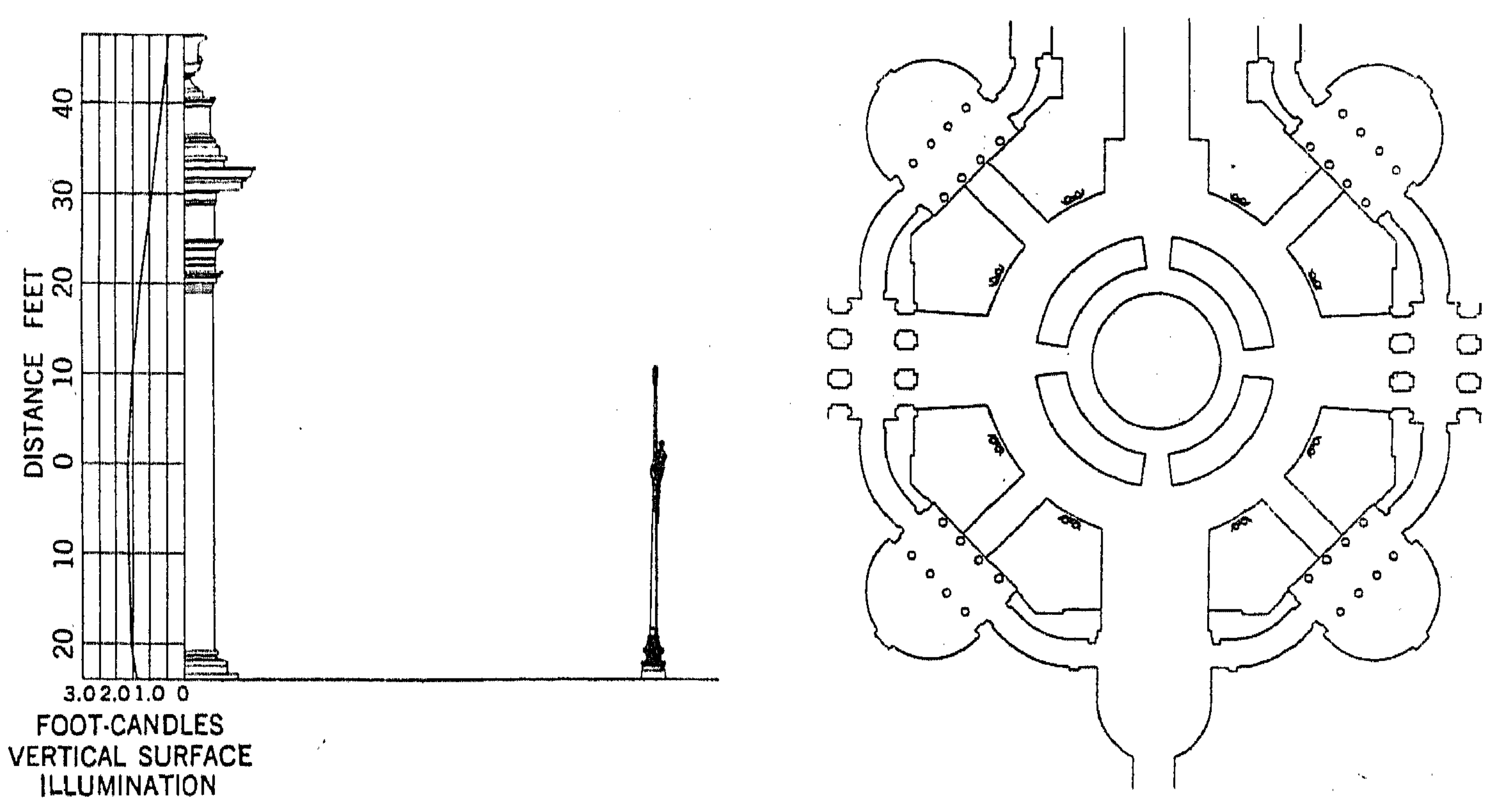


FIG. 8—VERTICAL SURFACE ILLUMINATION—COURT OF THE FOUR SEASONS

walls of the buildings and supplemented, with the banner standards, the flag illumination or sky line effect.

The flags on the buildings fronting on the Avenues of Palms and Progress were individually lighted by 13-in. (33-cm.) arc projectors, 100 units being used for this purpose. Economic reasons necessitated the designing of an incandescent projector for the lighting of the flags on the north and west walls and in the courts. This unit (Fig. 9) was constructed of an 11-in. (28-cm.) diameter parabolic mirror surrounded by a double row of small plain mirror panels which extended the parabola, thus increasing the efficiency. Two hundred projectors of this type with 500-watt mazda stereopticon lamps were used.

Electric Kaleidoscope. The electric kaleidoscope was designed to create exterior effects on the glass dome of the Palace of Horti-

culture, such as revolving bars, rings and spots in astronomical movements or the dissolving of colors from one shade or tint to another, without a sharp line of demarcation.

It consisted primarily of a battery of twelve 30-in. (762-mm.) arc projectors, arranged around a central structure as shown in the plan view, Fig. 10. The light from these twelve projectors passed through a common orifice in the top platform of the structure, at which point were located specially cut revolving interchangeable lenses. Before passing through the lenses the projected beams of light were intercepted by revolving color screens and shadow bars. Each one of these units was operated by an individual mechanism and independently of one another, as shown by the photographic and elevational view in Figs. 11 and 12.

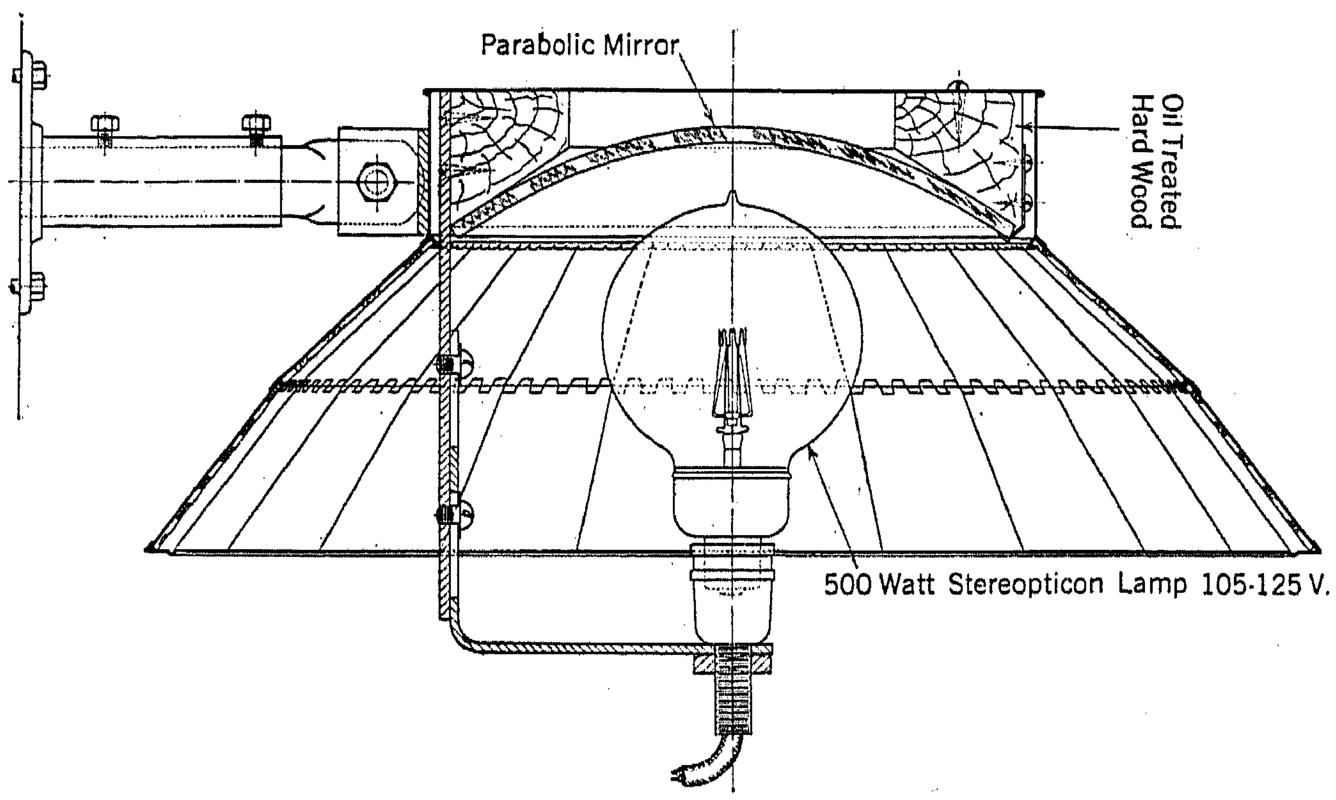


FIG.—9 FLAG LIGHTING UNIT

The different types of lenses were made up in sets of four separate quadrants (Fig. 13), which permitted the use of any combination of lenses desired at the same time. With this flexibility of lens combinations, together with the interchangeable color screens and shadow bars, it was possible to obtain a variety of effects.

N. B. The glass in the dome of the Palace of Horticulture was not in accordance with specifications. The results, while generally satisfactory, could not come up to anticipations, due to the lack of sufficient diffusion in the glass.

Indirect Lighting for Large Auditoriums. This lighting is applicable to large auditoriums or large places where concealed lighting is desired, but where the dome or ceiling construction does not permit the use of it. The system consists of placing a

battery of searchlights beneath the main floor and concentrating the beams on a diffusing plate in a central screened opening for re-distribution to the ceiling.

This was demonstrated by the installation in Festival Hall before the building was converted into a theater. Twelve 18-in. (457-mm.) projectors were used, giving a combined beam candle power of approximately 114,000,000. Inasmuch as a

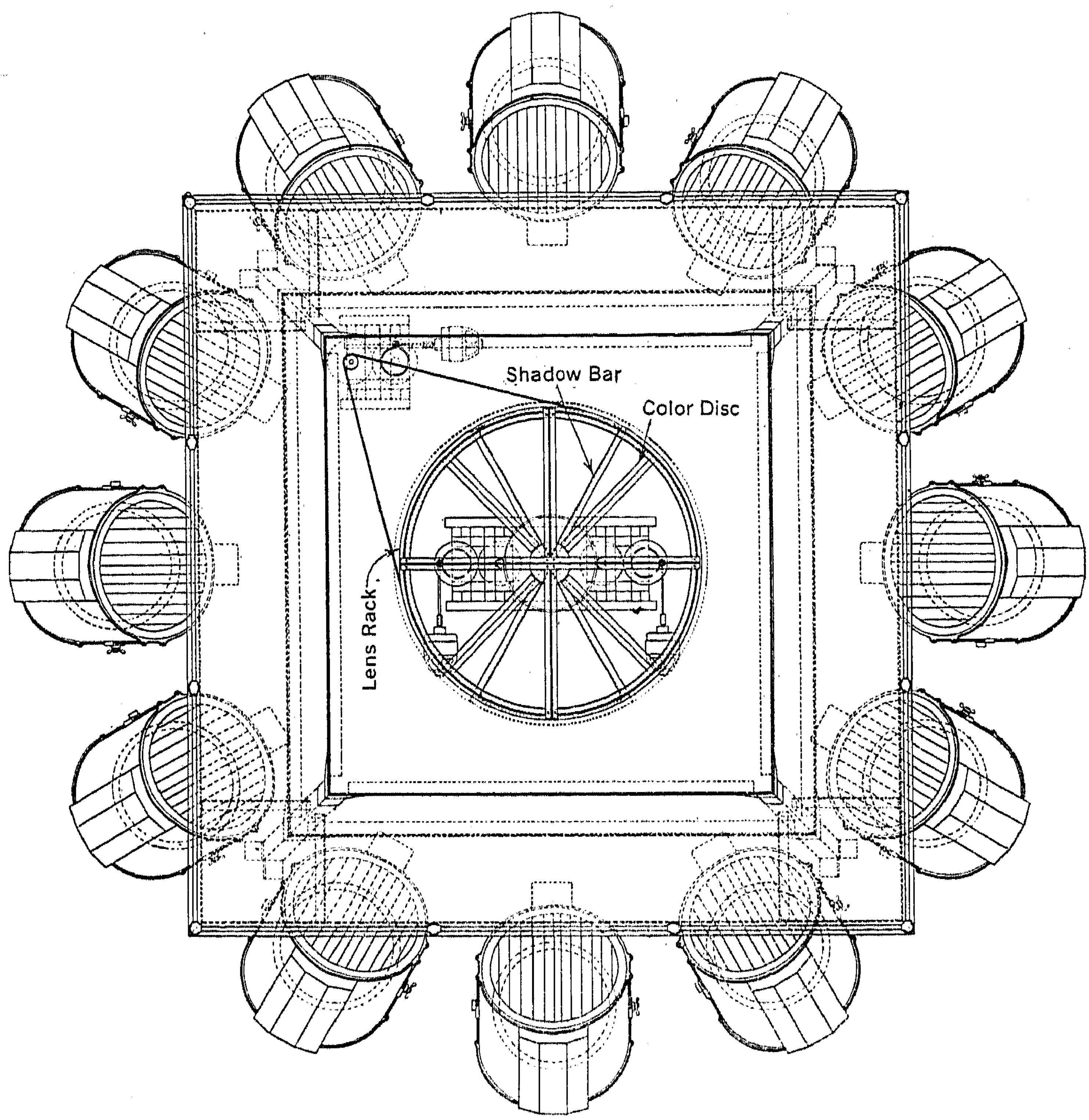


FIG. 10—PLAN VIEW OF ELECTRIC KALEIDOSCOPE—PALACE OF HORTICULTURE

large city sewer ran directly underneath the center of the building, it was necessary to locate the projectors in respect to it, as shown in Figs. 14 and 15. Fig. 16 shows a preliminary calculated illumination curve for the ceiling and walls.

Non-Glare Art Gallery Illumination. In the lighting of the Palace of Fine Arts a system was designed whereby the lamps were placed above the skylight and around the perimeter. By

the combination of a suitable angle reflector and the proper diffusion glass a good general distribution was obtained on the hanging surfaces, and specular reflection was further reduced

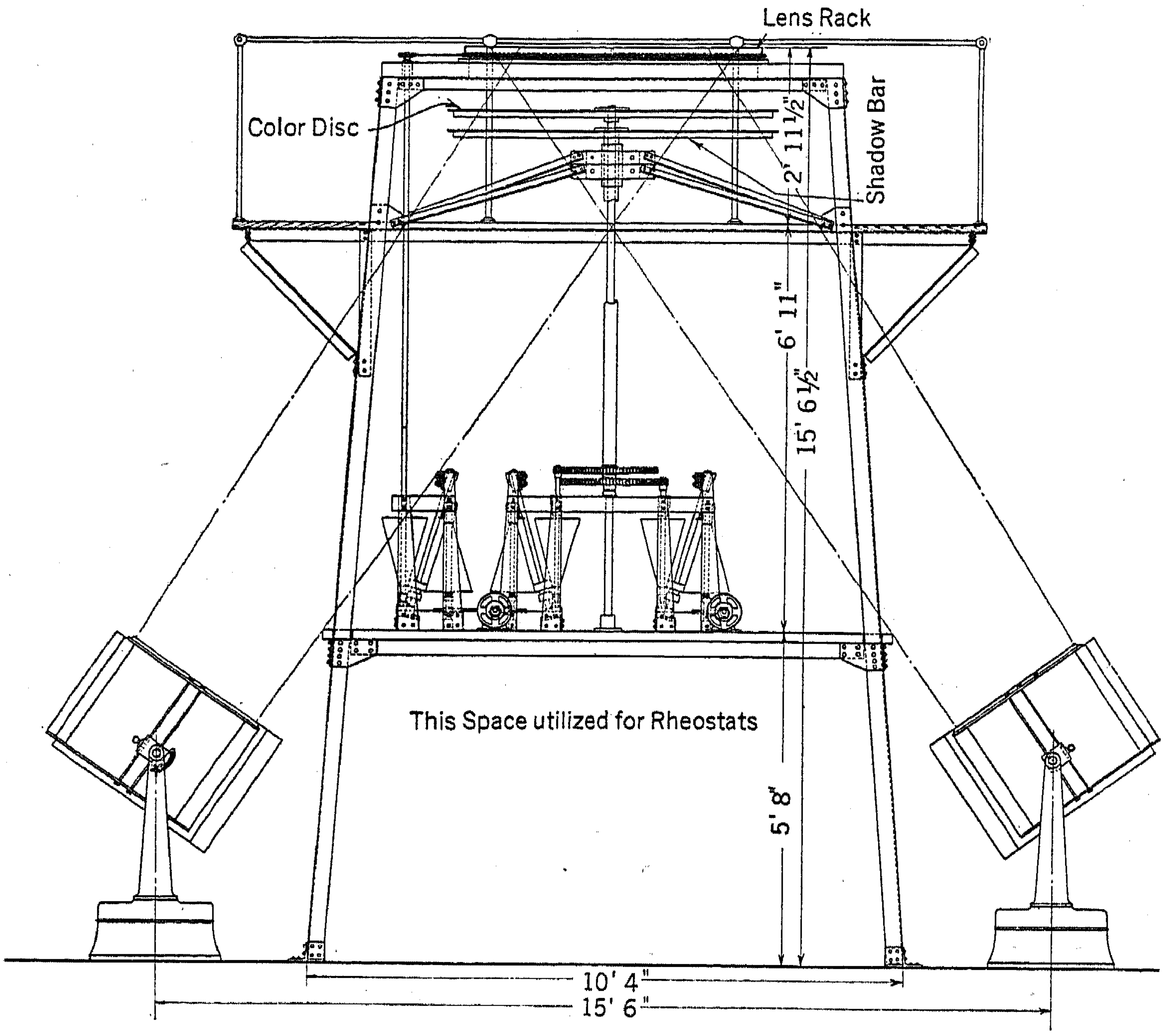


FIG. 11—ELEVATION OF ELECTRIC COLOR KALEIDOSCOPE—PALACE OF HORTICULTURE

by the use of shadow curtains on the under side of the skylight. For economic reasons the shadow curtains were finally omitted. This system of lighting has considerable advantage over the

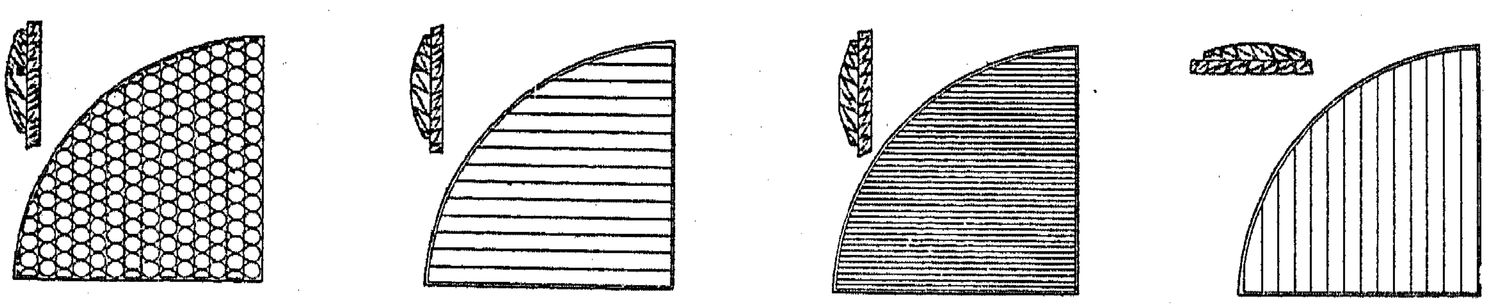
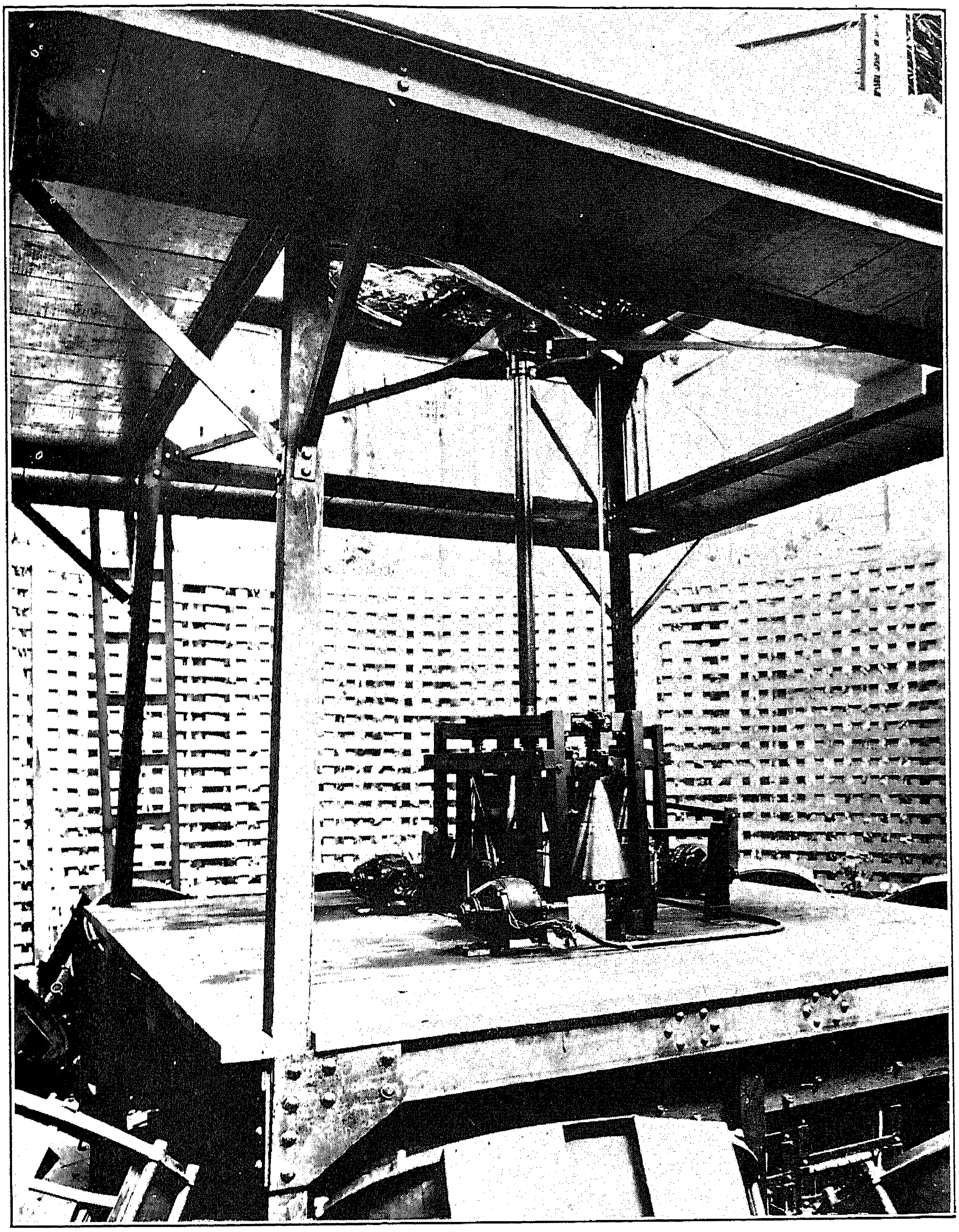


FIG. 13—LENS QUADRANTS FOR ELECTRIC KALEIDOSCOPE—PALACE OF HORTICULTURE

common practise of distributing lights generally over the skylight, which produces strong specular reflection and also gives the greatest illumination on the floor in the center of the room, where it is least desired.



[RYAN]

FIG. 12—ELECTRIC COLOR KALEIDOSCOPE, PALACE OF HORTICULTURE

[RYAN]

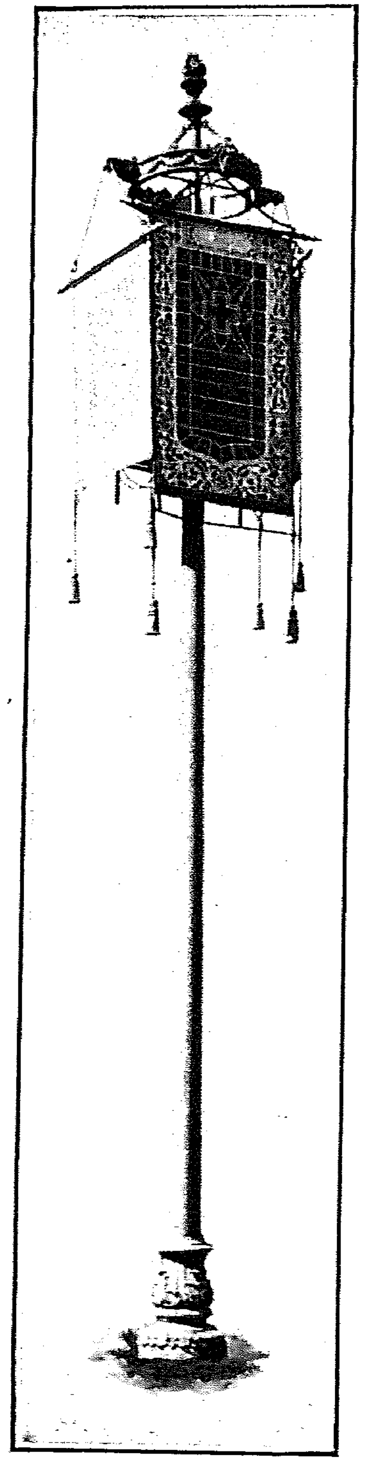


FIG. 26—FRONT VIEW OF FIVE AND SEVEN-LIGHT LUMINOUS ARC LAMP BANNER STANDARD—HEIGHT 35 FEET

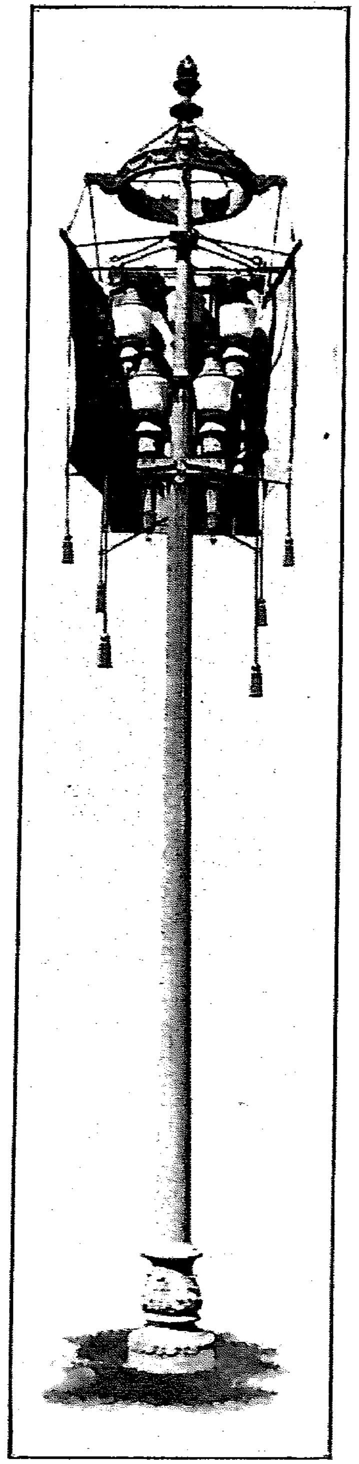


FIG. 27—REAR VIEW OF FIVE-LIGHT LUMINOUS ARC LAMP BANNER STANDARD, HEIGHT, 35 FEET

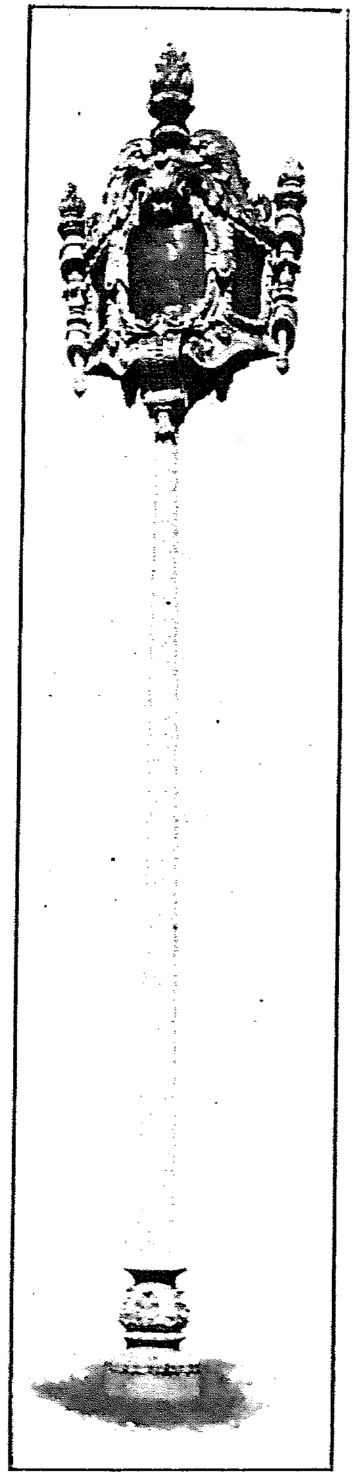


FIG. 28—THREE-LIGHT LUMINOUS ARC LAMP CARTOUCHE STANDARD, HEIGHT 35 FEET

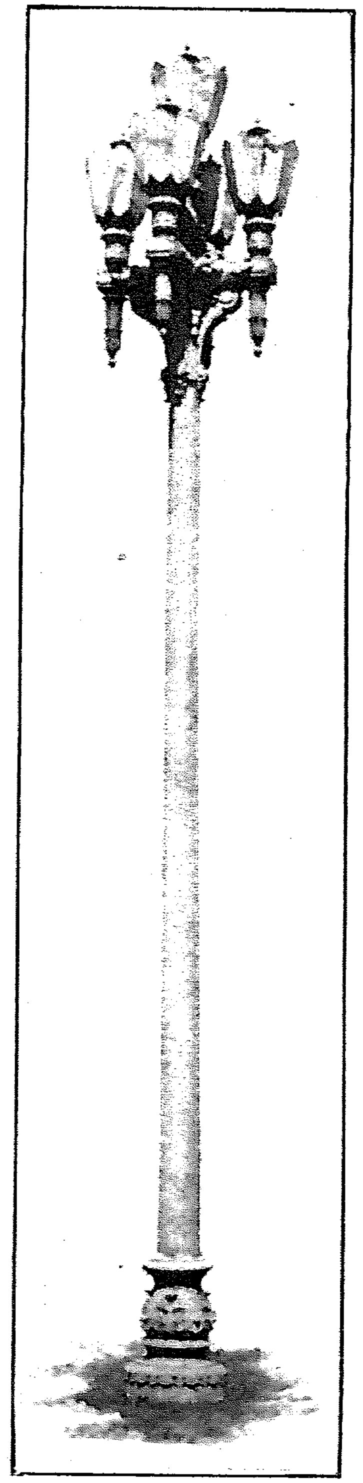


FIG. 29—FIVE LIGHT LUMINOUS ARC LAMP BAND CONCOURSE STANDARD, HEIGHT 35 FEET

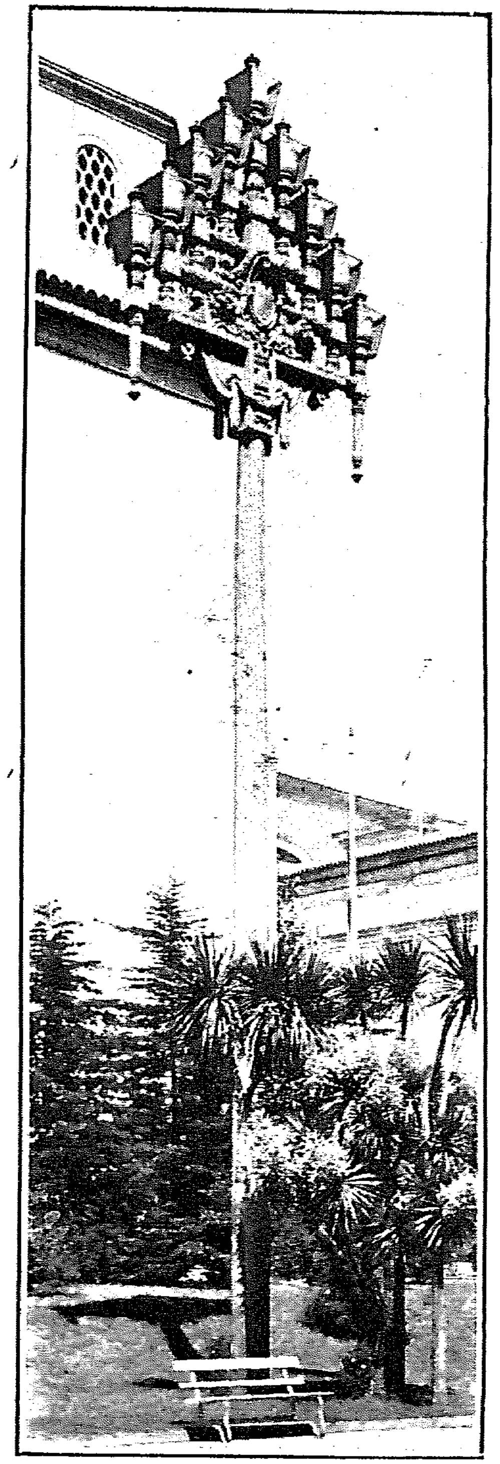


FIG. 30—NINE-LIGHT LUMINOUS ARC STANDARD, HEIGHT 35 FEET

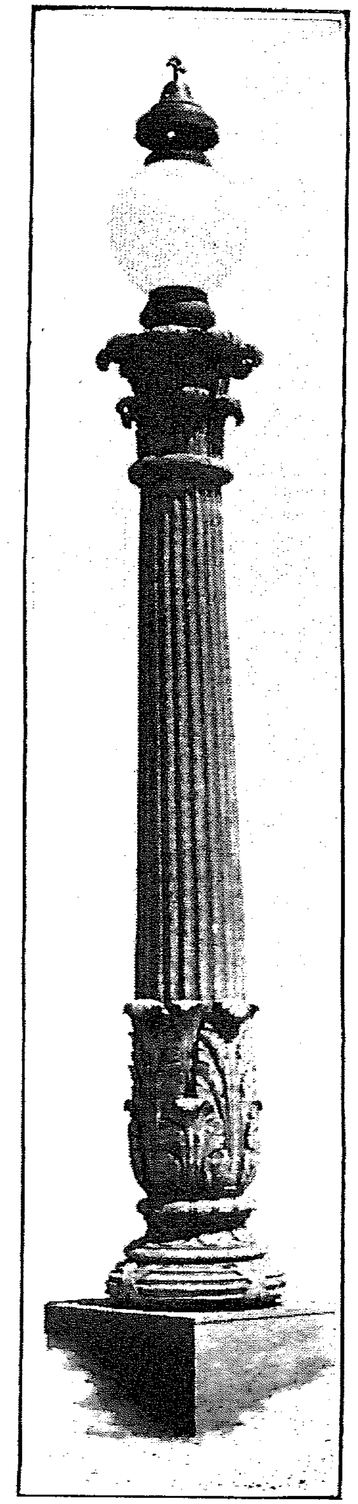
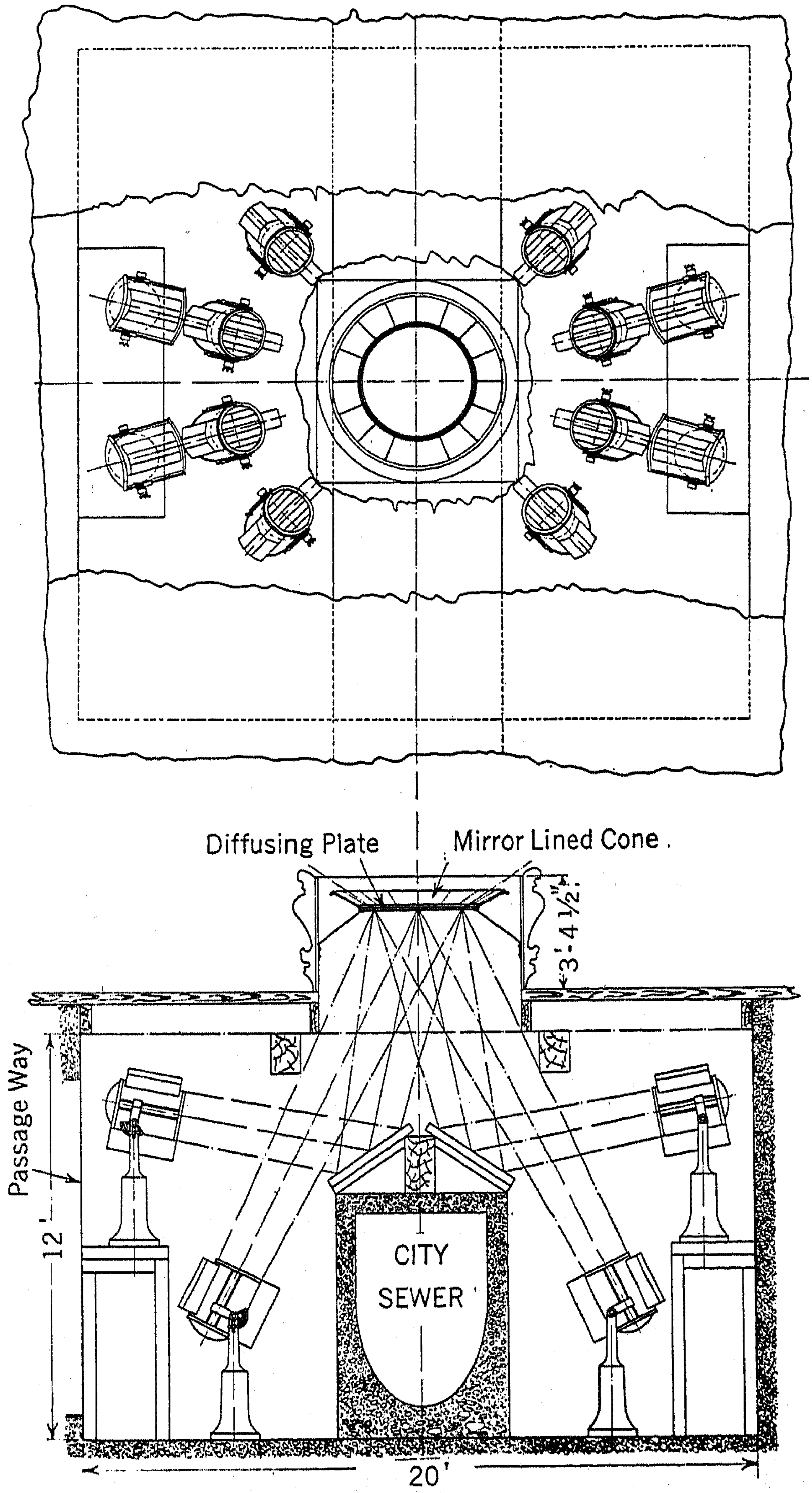


FIG. 31—MARINA TYPE PENN GLOBE HIGH PRESSURE GAS ARC STANDARD

High Bay Lighting. For the illumination of high bays, large units, singly or in pairs, were placed at the maximum height in special reflectors (Fig. 17), designed to prevent waste illumi-



FIGS. 14 AND 15—PLAN OF INDIRECT LIGHTING—FESTIVAL HALL

nation on vertical surfaces and obtain maximum intensity on the floor with relatively uniform distribution, and absence of spots. The main buildings of the Exposition were lighted in this way, using only one-tenth watt per square foot with the mazda

B lamps, resulting in approximately one-half foot-candle average illumination for lamp heights, in some cases over 100 ft. (30.5 m.) above the floor. This illumination was primarily for janitor and police service, exhibitors being required to furnish their own lighting.

"Life Within" Effects. At previous expositions the windows were dark at night, producing a gloomy effect. In addition to lighting up the general architecture with proper relative values of illumination, lights were placed behind the windows which had been glazed with diffusing glassware, having a good daylight

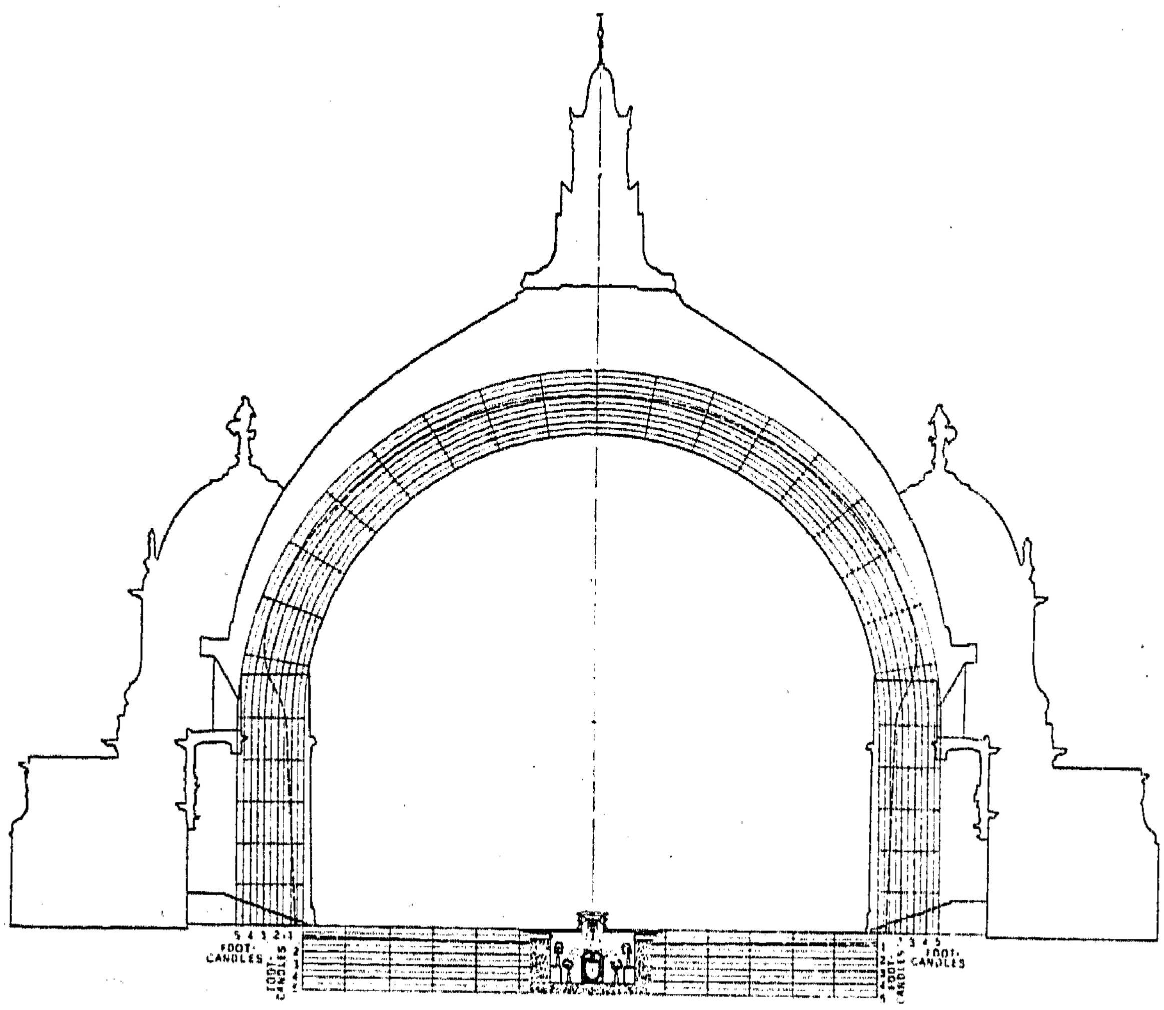


FIG. 16—INTERIOR SURFACE ILLUMINATION—FESTIVAL HALL

texture. In some cases, for the introduction of color, the diffusion was increased by painting the glass. The general effect at night was of festivity, of "life within", which added animation to the general charm of the Exposition, particularly when viewed from an elevation.

Lamps for window lighting ranged in size from 60 to 250 watts, depending upon the size of the window to be lighted. The clerestory windows which were unpainted, were lighted by 150-watt lamps dipped in orange lacquer. Practically all of the entrance windows were painted, and these were illuminated by clear lamps in sheet tin extensive reflectors. All of the window lights, with the exception of those in the domes, were suspended on drop cords. The dome windows were lighted by 250-watt

lamps in angle reflectors mounted five feet to the rear of the windows.

Combination Fountain and Light Sources. The original fountains of the Rising and Setting Sun, in the Court of the Universe, designed by McKim, Mead and White, were 65 ft. (20 m.) high. In order to accommodate the lighting the architects increased the height to approximately 95 ft. (29 m.) and constructed them as shown in Fig. 18. The flutes of the 31-ft. (9.4-m.) section beginning at a point 37 ft. (11.3 m.) above the ground surface, were made of $\frac{1}{4}$-in. (6.35-mm.) thick special diffusing glass, backed up by a secondary sheet of sand-blasted glass to eliminate structural shadows. By arranging 96 1500-watt mazda lamps in twelve rows of eight each, this section of the fountain became an immense candle or light source at night. To dissipate the

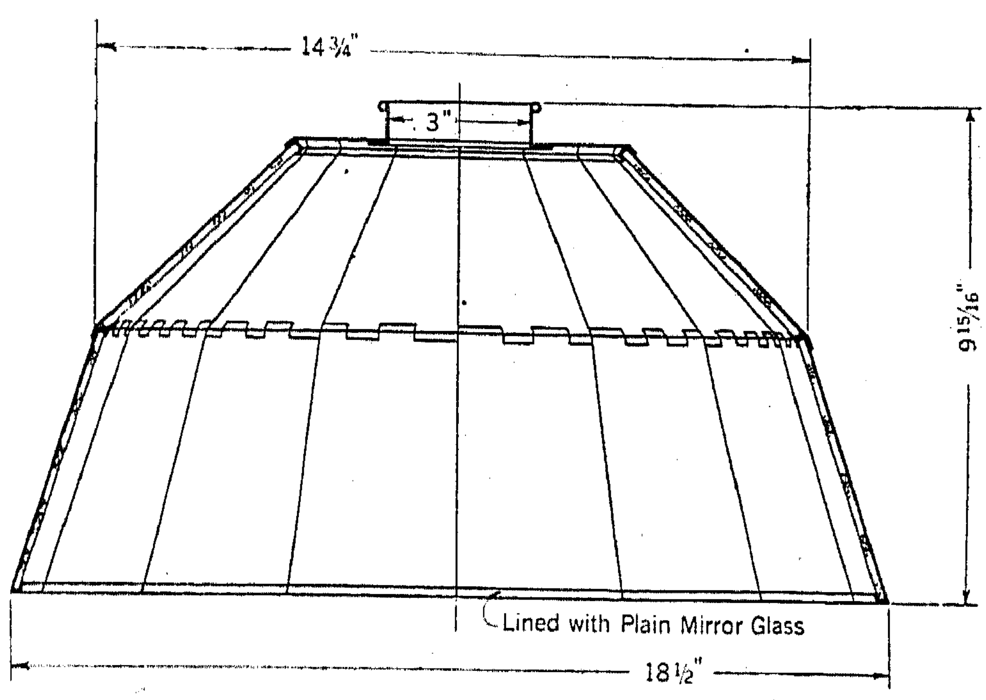


FIG. 17—HIGH BAY REFLECTOR

heat generated by this bank of lamps, consuming 144 kw., a 5-h.p. blower was installed in the base of each fountain and created a forced cooling draft which was discharged from air vents at the base of the ball surmounting the shaft. This ball was lighted from the inside by eight 250-watt mazda lamps. Notwithstanding the fact that the 96 lamps in each one of these fountains had a combined initial spherical candle power of approximately one quarter of a million, the intrinsic brilliancy was relatively low and did not cause disagreeable eye strain. The horizontal and vertical surfaces illuminated by the two fountains were approximately one-half million square feet (46,450 sq. m.).

To carry out the night effect of these fountains, the figure surmounting the glass ball was lighted by two 6-volt, 108-watt incandescent spot-lights located on the roofs of the adjoining

buildings. The sculptured friezes above the two basins were lighted by twenty-four 150-watt lamps in weatherproof solid body angular reflectors submerged in each basin (Fig. 19). The isolux chart in Fig. 20 shows the initial calculated values for the Court of the Universe and the North Approach. The isolux curves shown in the court proper were calculated from the

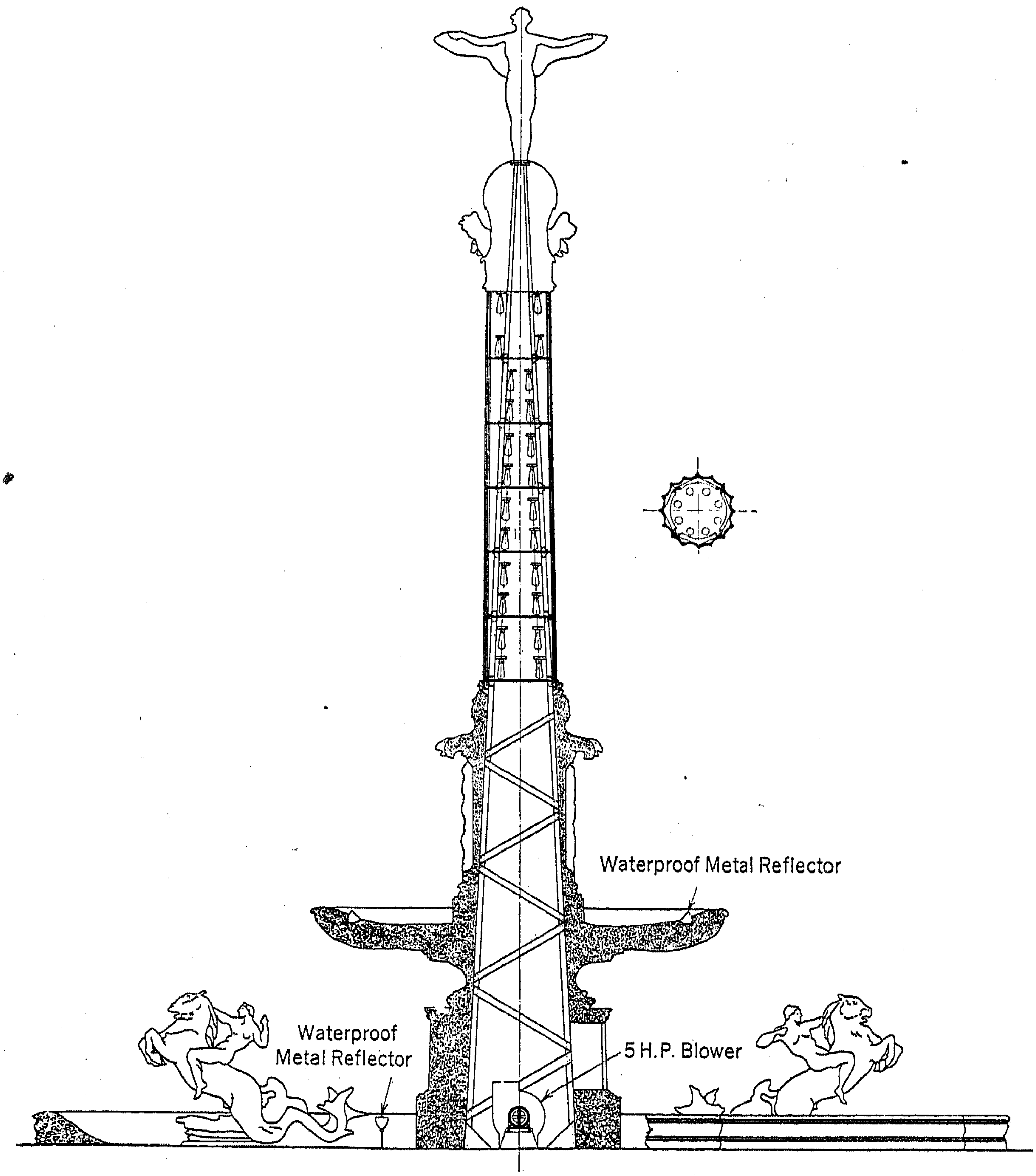


FIG. 18—ELEVATION OF FOUNTAIN IN THE COURT OF THE UNIVERSE

initial candle power values of the 1500-watt lamps in the fountains. Subsequently, for economic reasons, the illumination was reduced by lowering the voltage on the lamps in order to lengthen their life. The approach to this court was lighted by sixteen 1500-watt lamps, installed in a shell design type of standard. These standards were located on the balustrade

surrounding the central pool and flood-lighted the building facade, the promenade receiving most of the light by reflection from the large columns and the overhanging cornice.

Relief Wall Lighting by Concealed Sources. The practise of past expositions has been to place exposed lamps on the rear of the columns to light the back walls. This resulted in lines of light being visible from almost any point of view, which detracted from the appearance of the columns.

In the lighting of the colonnades in the Court of the Universe and the Court of the Four Seasons, three column cups were sunk into the central flute in the rear of each column, in the case of

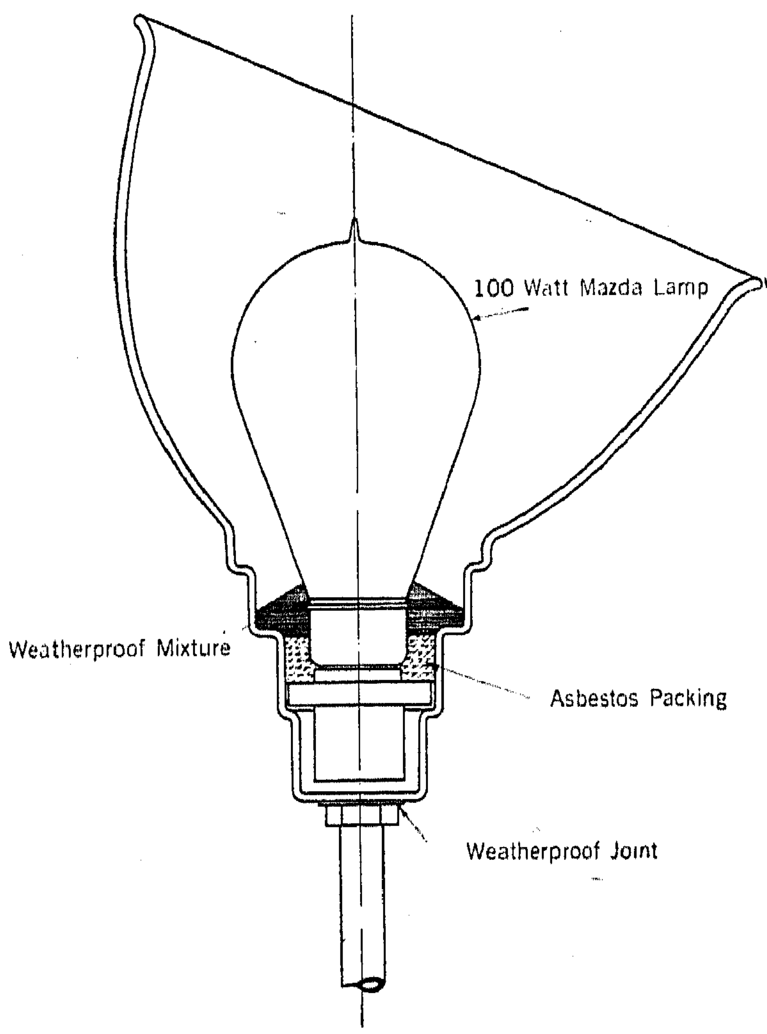


FIG. 19—CROSS SECTION OF ANGULAR WEATHER-PROOFED REFLECTOR

the former, and on the center line of the plain columns in the latter case. These column cups were of pressed opal glass and embedded in the columns (Fig. 21) and spaced 10, 22 and 34 ft. (3.05, 6.7 and 10.4 m.), respectively, above the floor level of the colonnade. Fig. 22 shows the distribution characteristics of this type of cup with a 150-watt clear mazda lamp. The walls were illuminated with a rising light resulting in a total absence of specular reflection and an average illumination on the wall surface of approximately 4 foot-candles. The illumination curve (Fig. 23) shows the values obtained on a vertical line directly back of one of the columns and curve *a-a*, Fig. 20, shows the calculated illumination on a horizontal line along the wall

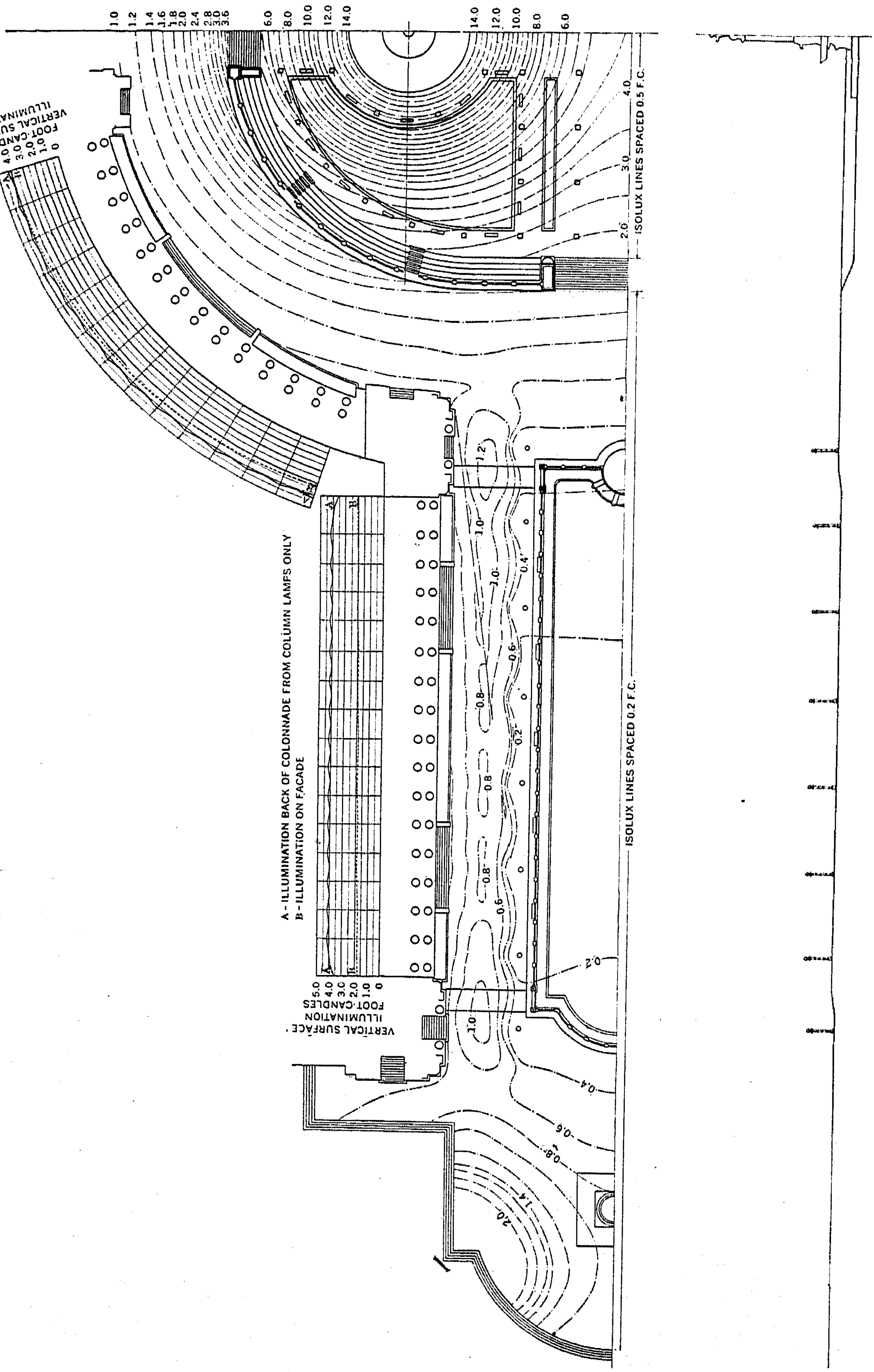


FIG. 20—ISOLUX AND ILLUMINATION DIAGRAM—COURT OF THE UNIVERSE AND NORTH APPROACH

surface 6 ft. (183 cm.) above the floor level. While the column cups were invisible from any part of the court proper, when viewed from the rear of the colonnade they appeared like great drops of molten metal, producing an unusual effect.

The Creation of Mystery in the Lighting of Open Courts. In designing the Court of Abundance, the architect wished to impress as far as possible a feeling of mystery, or something carrying the mind down through the ages. This effect was strengthened

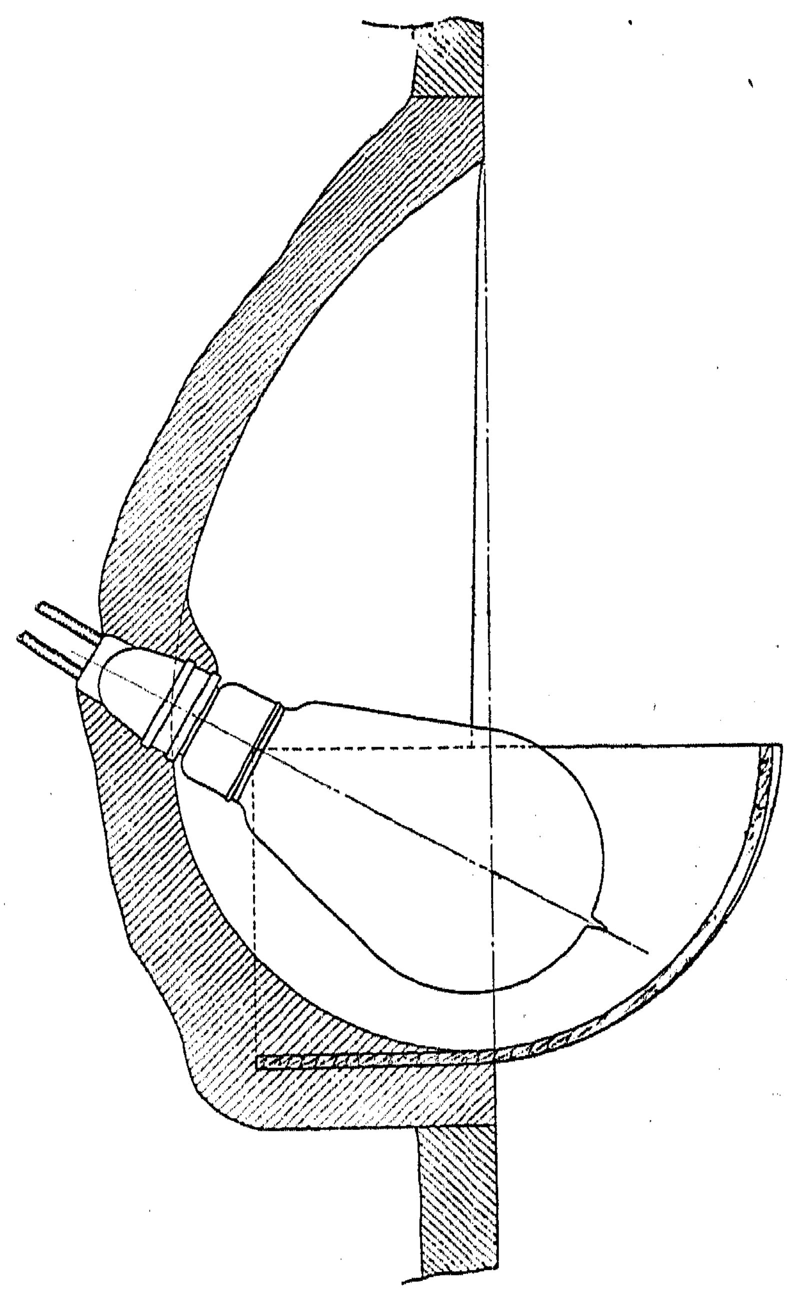


FIG. 21—CROSS SECTION OF COLUMN CUP

by a harmonious blending of illumination by searchlights, incandescent lights, gas flambeaux and illuminated steam.

The general illumination of this court came from three sources: the snow crystal standards, the cloister lanterns and the gas flambeaux. The snow crystal standard, or as it was sometimes called, the "sunburst" (because of the design suggestion), contained over 600 15-watt round globe orange-dipped incandescent lamps. There were two of these standards in the main court and four in the north approach to this court. On either side and at the spring line of each cloister arch there was suspended a

Gothic lantern with orange glass panels. In addition to lighting the cloister and the adjacent gardens these lanterns were especially valuable for their decorativeness. The gas flambeaux were formed by four rising serpents hissing fire into a flaming caldron. There were six of these located in the court proper and sixteen in the north approach to the court.

The additional "effect" lighting came from the boiling steam-electric caldrons flanking the east and west entrances, the steam-electric torches of the organ tower, the flood and relief lighting of this tower and the illuminated steam issuing from the ball of the central fountain. The steam used in producing these effects

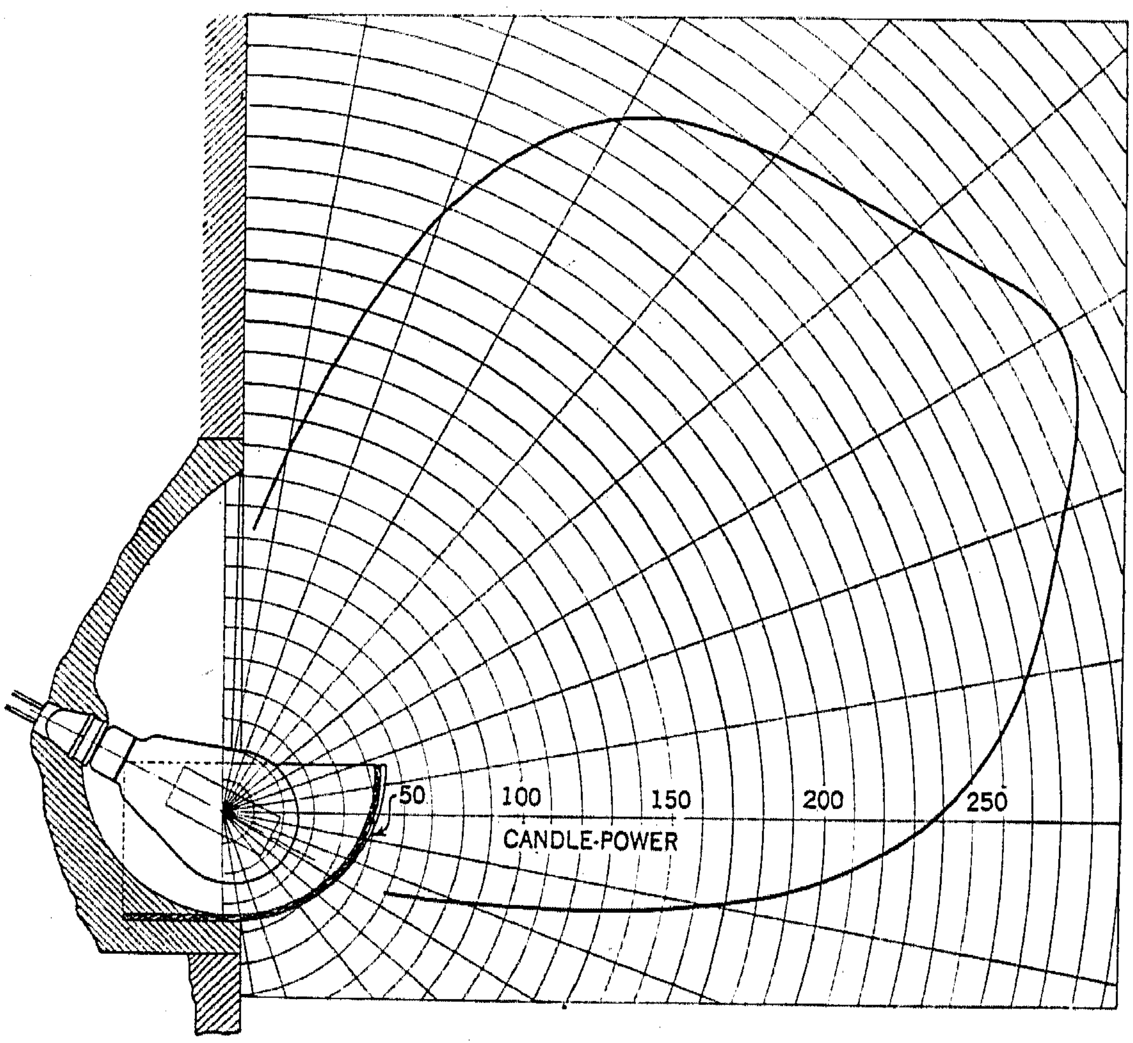


FIG. 22—CANDLE-POWER DISTRIBUTION OF 150-WATT MAZDA LAMP IN COLUMN CUP

was delivered by a 15-h.p. gas-fired boiler located in the base of the organ tower. The color tone of the court at night ranged from orange to rose red.

Flood and Relief Lighting to Obtain Artistic Reflections. In order to create reflections of unusual beauty, especially in the illumination of the Palace of Fine Arts, banks of searchlights with diverging doors of varying degrees, designed to meet the requirements, were used to flood-light the building, producing what might popularly be called "triple moonlight". This was supplemented by concealed yellow incandescent light in the soffits of the cornices to the rear of the columns, thereby providing three effects: flood lighting, relief lighting, or the com

bination of both. Variety was obtained for special occasions by the introduction of color into the searchlight beams.

Concealed Cascade Lighting. In the lighting of cascades at previous expositions, either the source has been visible, or a reflection of the source, which is equally undesirable. The cascades in the Court of the Four Seasons were so illuminated that neither the light sources nor their images in the water were visible. By the use of green light on the rear surface and red and orange on the front, the effect of iridescence was produced.

Preservation of Curvature and Detail in Relief. The preservation of the curvature and detail in relief was accomplished by lights

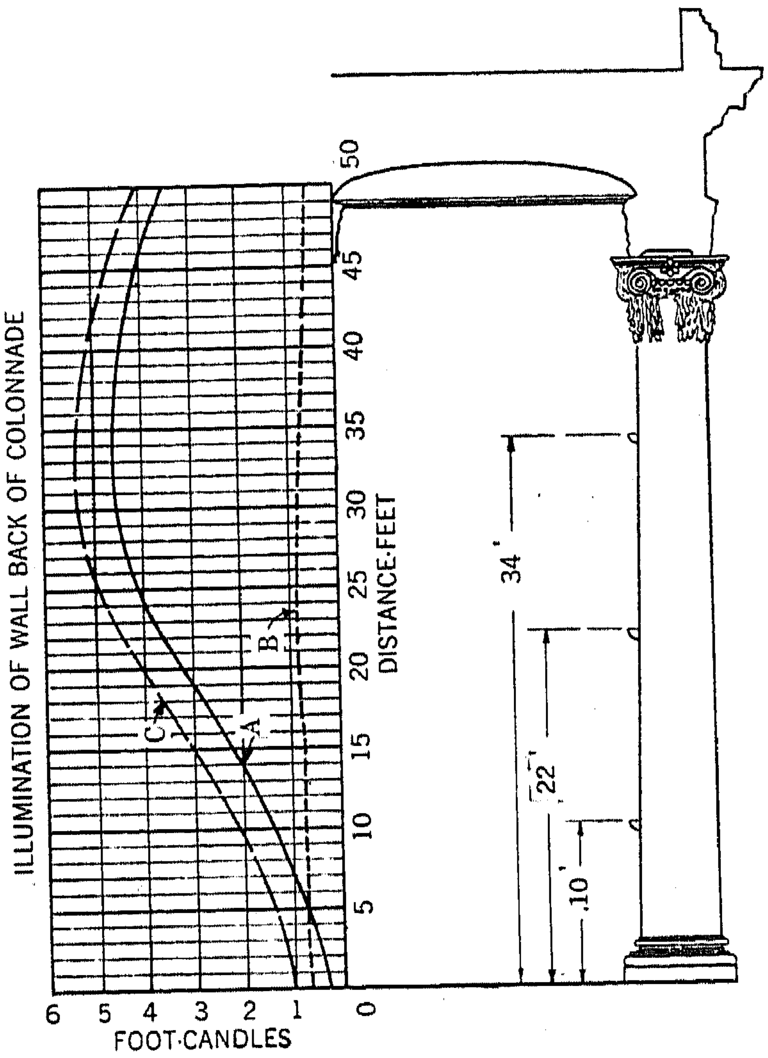


FIG. 23—COURT OF FOUR SEASONS—COLONNADE WALL ILLUMINATION
A—150-watt Mazda lamps in column cups. *B*—2-light luminous arc banner standards. *C*—Column cups and banner standards.

of different strengths and colors thrown from different or opposite directions on the same object. For example, to preserve the curvature of the walls and the relief of the figures in the four season niches of the Court of Four Seasons, 50 100-watt mazda lamps ranging from red to canary, in metal reflectors, were installed on the top rear side of the niche colonnade (Fig. 24).

The main arches throughout the Exposition were lighted with concealed red light on one side and pale lemon yellow on the other. All of the lamps used in any one arch were of the same initial candle power, but, due to the difference in absorption of the two colors, the light from one side was of much greater intensity than from the other, thereby preserving the curvature and depth in relief.

Changeability of Lighting Effects. Three-hundred and seventy-three arc searchlights, ranging in size from 13 to 36 in. (33 to 91.4 cm.), were used throughout the Exposition, and 450 concentrated-filament mazda searchlights, forming a so-called "mosquito fleet", were also employed. By the use of colored gelatine screens, it was an easy matter on short notice to change the entire aspect of the Exposition by coloring the lights on the flags, towers and buildings (flooded with searchlights) as well as the rays of the scintillator. For instance, on the 17th of March, the Exposition, including the canopy above, was illumined in green tones; on Orange Day, orange prevailed; on the "Nine Years After" anniversary of the burning of San Francisco, red was the predominating color; and on Santa Clara Day, red and

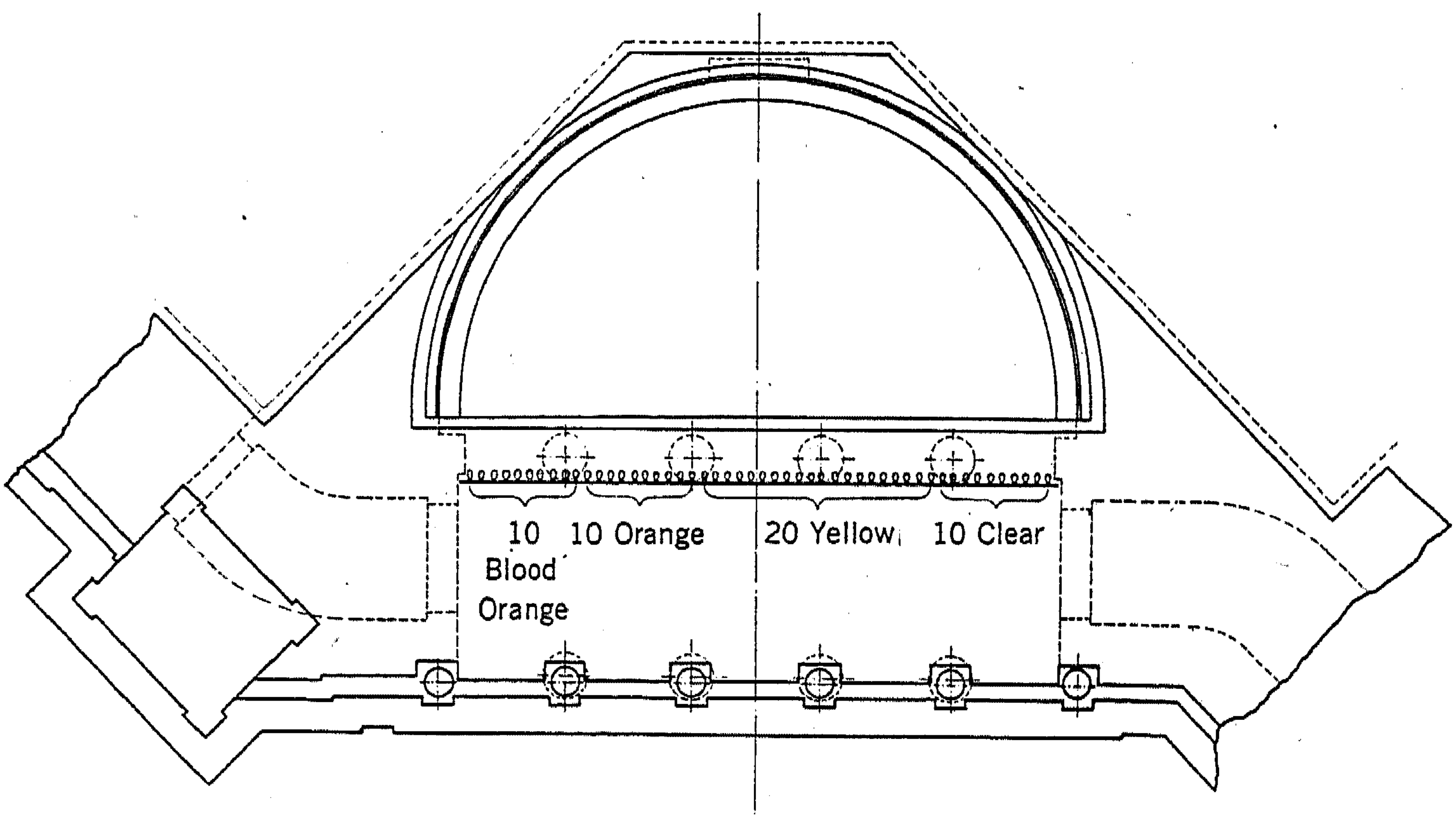


FIG. 24—SEASON NICHE LIGHTING—COURT OF FOUR SEASONS

white, the colors of the university, were used—thereby making it possible for the first time to introduce considerable variety on short notice, and at nominal expense, into the illumination effects of an international exposition.

In conclusion, the lighting consisted primarily of direct, masked, concealed and projected effects, created by a harmonious blending of luminous arcs, searchlights, mazda lamps and gas lights.

The high-current luminous arc lamp was selected for general flood lighting of the facades, lawns and shrubbery, on account of the white quality, high efficiency and relatively low maintenance cost where great quantities of light were required.

The searchlights were used for illuminating towers and mina-

rets, flags and other features where concentration and high intensity were necessary.

Mazda lamps, in all sizes from 10 to 1500 watts, were employed

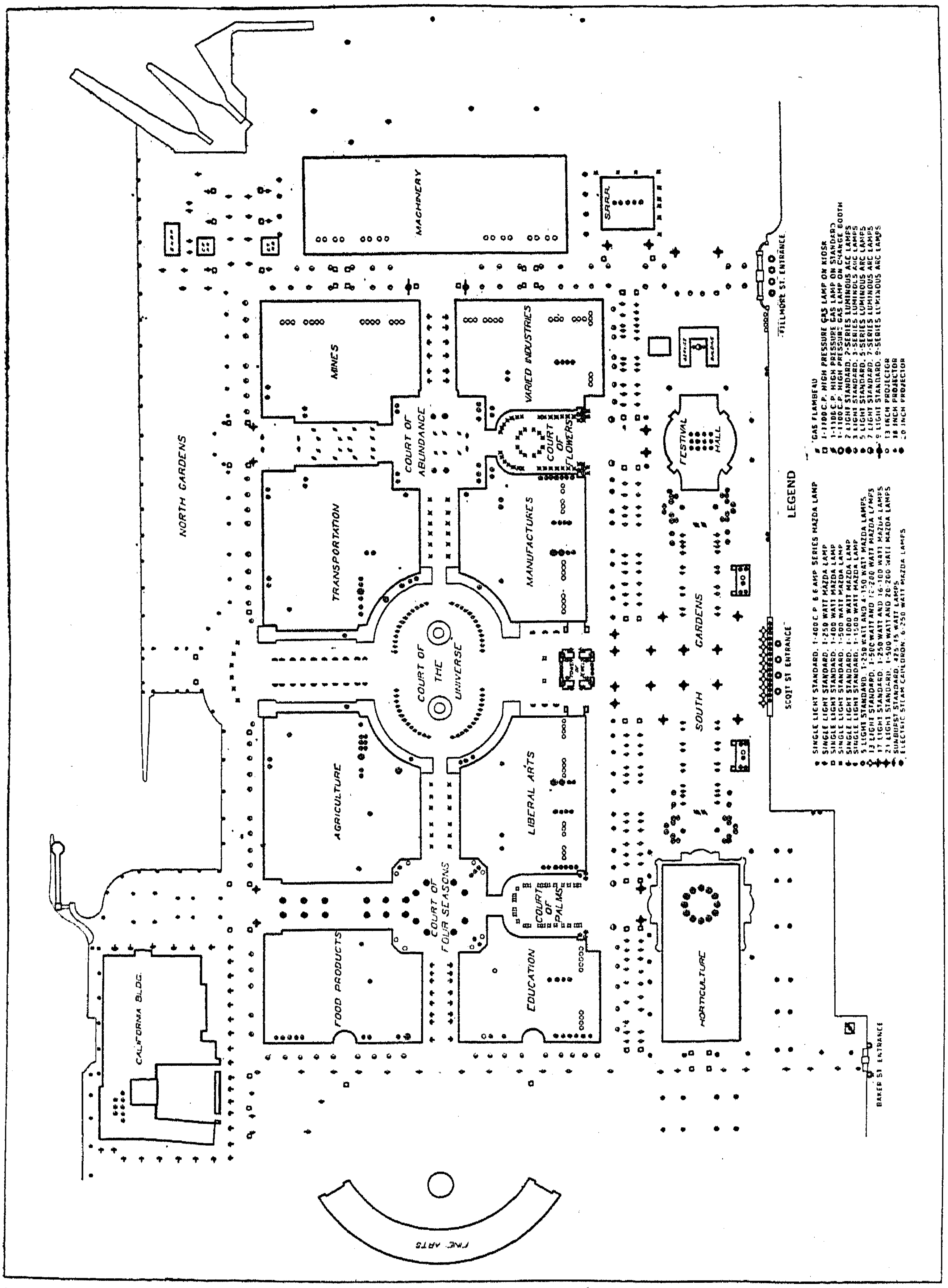


FIG. 25—GROUND AND BUILDING PLAN OF MAIN EXHIBIT PALACES
Showing Location of Incandescent and Arc Standards, Gas Emergency Lights and Searchlights

generally throughout the Exposition, especially where space was limited, where warm, normal tones were required and flexibility was of fundamental importance.

High-pressure gas lighting played an important part in street

lighting in the Foreign and State sections, low-pressure gas for emergency purposes, and gas flambeaux for special effects.

The unusual consideration given to esthetics and the suppression of high intrinsic brilliancy effects, naturally introduced certain features in the lighting which, from a purely engineering point of view, would be regarded as inefficient. Taken as a whole from the point of effects obtained, initial cost, maintenance and general efficiency, it was broadly conceded that the illumination of the Panama-Pacific International Exposition surpassed that of all previous expositions.

GENERAL LIGHTING AND POWER DATA

PANAMA-PACIFIC INTERNATIONAL EXPOSITION—1915

		Total kw.
Incandescents installed and operated by Exposition Co. (approx.)		3650
Luminous Arcs " " " " " "		548
Searchlights " " " " " "		1792
Pumps " " " " " "		750
Total Power and Light " " " " "		6740
State and Foreign Buildings	Light inside	716
" " " "	Light outside	134
" " " "	Power	75
Total Power and Light—States and Foreign Sites		925
ZONE	Light inside	1352
	Light outside	676
	Power	875
Total Power and Light—Zone		2903
EXHIBITORS	D-C. Light	45
	D-C. Power	618
	A-C. Light	1293
	A-C. Power	1430
Total Power and Light—Exhibitors		3386
Total Connected Load at Exposition		13954
Peak Load, occurred February 20th, 7:45 p. m.		8200
Average Peak		7880

INSTALLED AND OPERATED BY EXPOSITION COMPANY

	Number
Mazda incandescent outlets (approx.)	35000
Mazda incandescent standards	588
6.6-ampere ornamental luminous arcs	800
Luminous arc standards	208
High-pressure gas "arcs"	275
" " " " (standards)	205
Low-pressure gas lamps	232
Searchlights (100 13-in.; 200 18-in.; 25 30-in.; 48 36-in.)	373
Total pieces of illuminating glassware (approx.)	5000

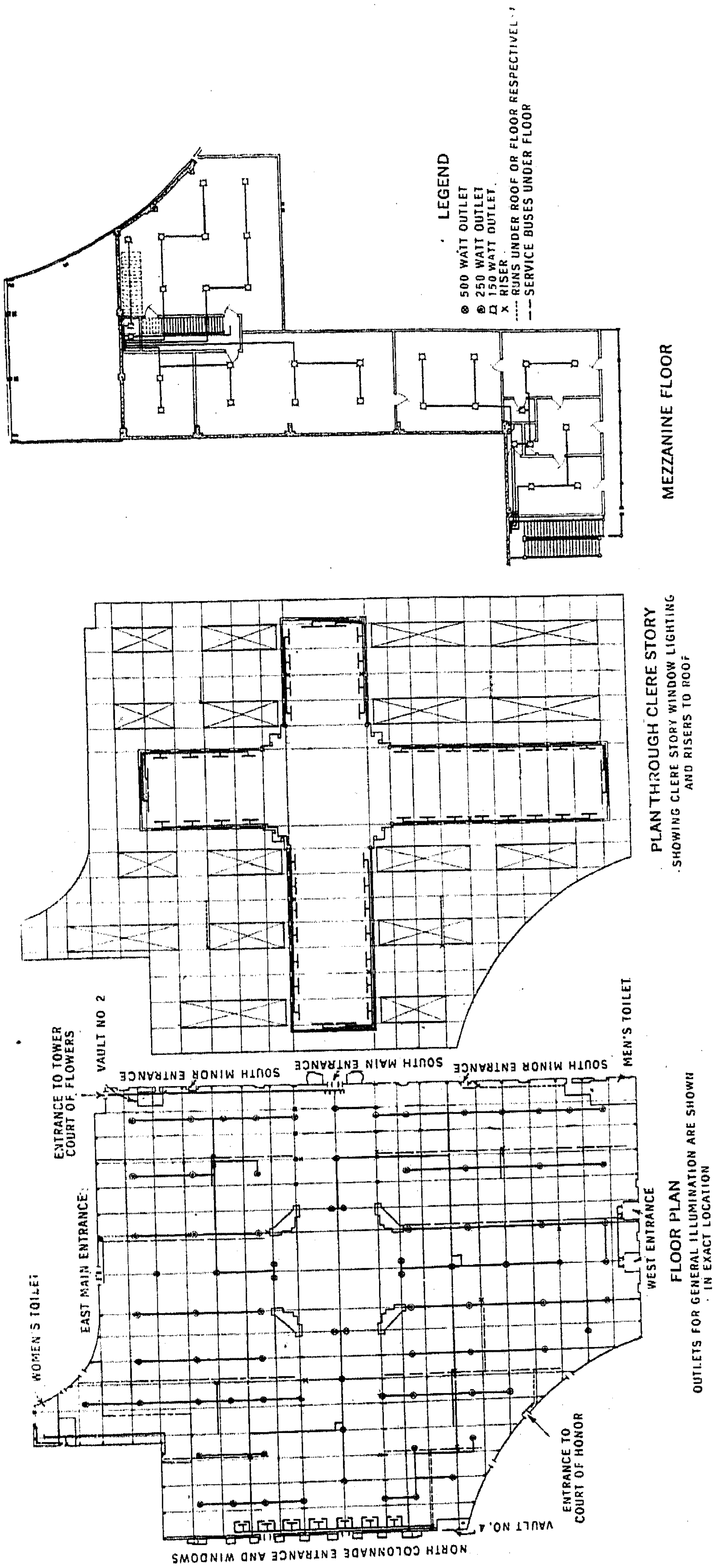


FIG. 32—OUTLET AND WIRING DIAGRAM—PALACE OF MANUFACTURES

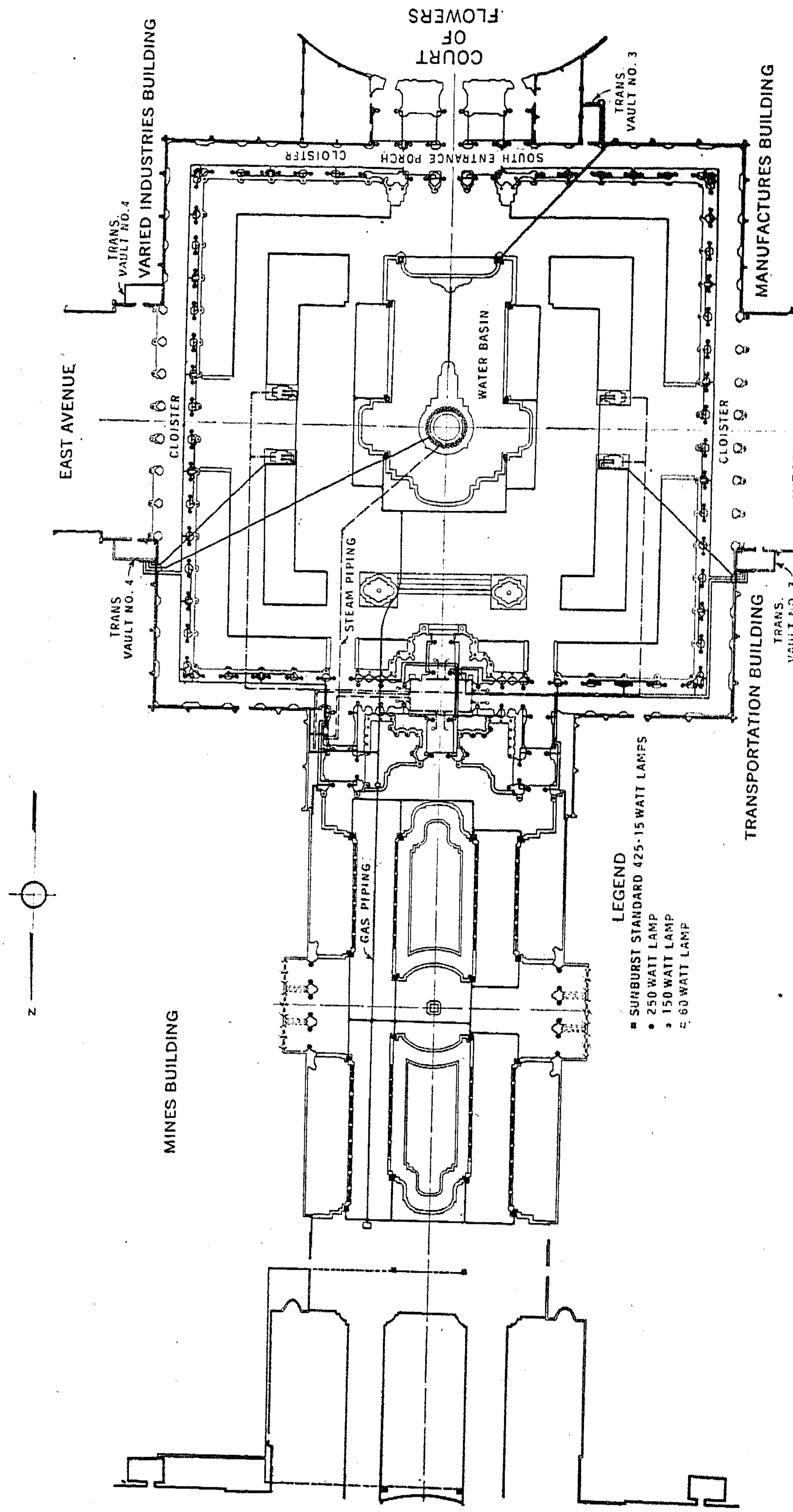
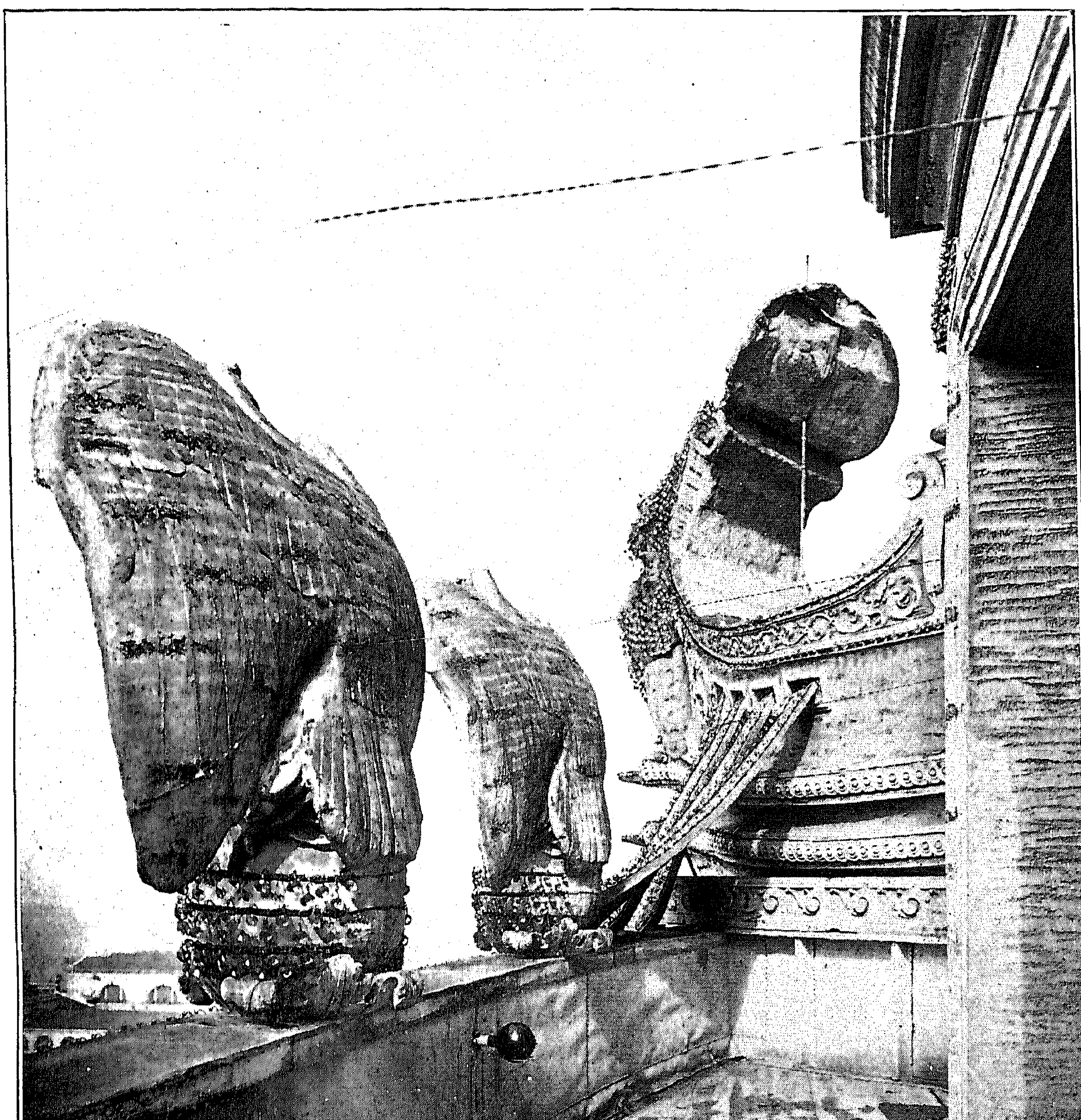


FIG. 33—OUTLET, WIRING, STEAM AND GAS DIAGRAM—COURT OF ABUNDANCE



[RYAN]

FIG. 34—VIEW OF TOWER OF JEWELS SHOWING METHOD OF SUSPENDING JEWELS AND RED LAMP FOR RELIEF LIGHTING

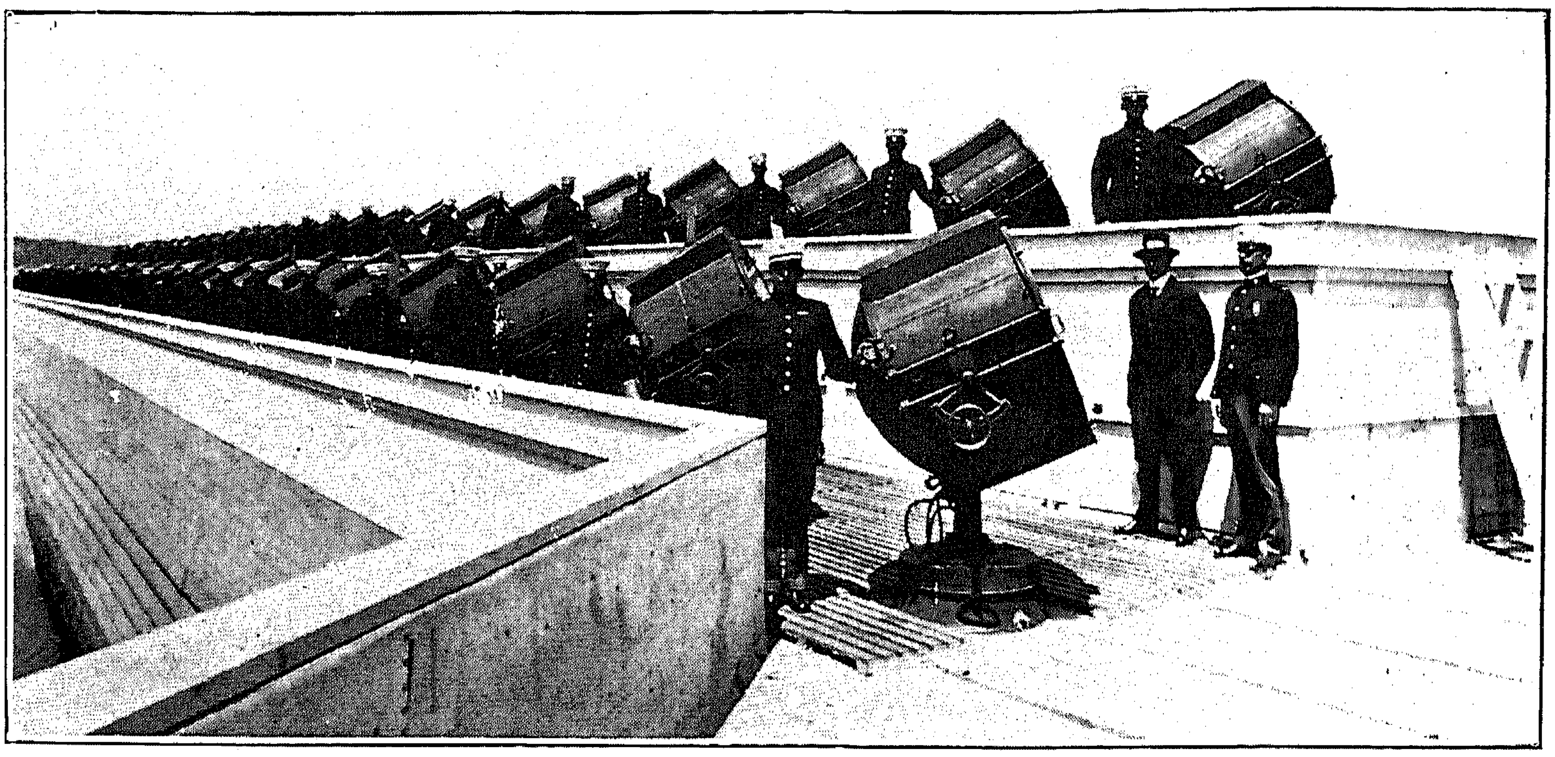


FIG. 35—ELECTRIC—COLOR—STEAM—SCINTILLATOR

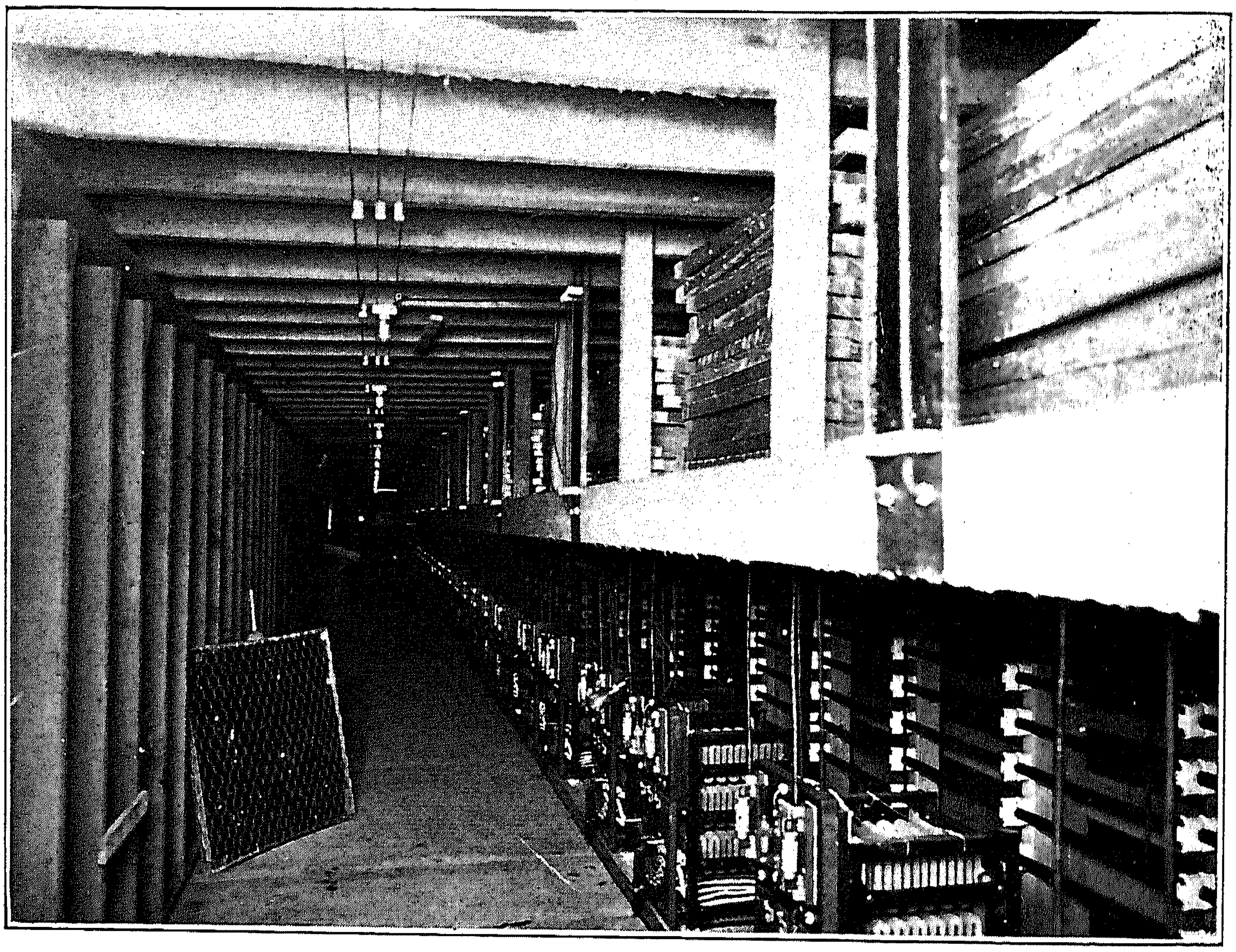


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FIG. 36—INTERIOR VIEW OF SCINTILLATOR PIER

This shows color screens resistances and distribution circuits.

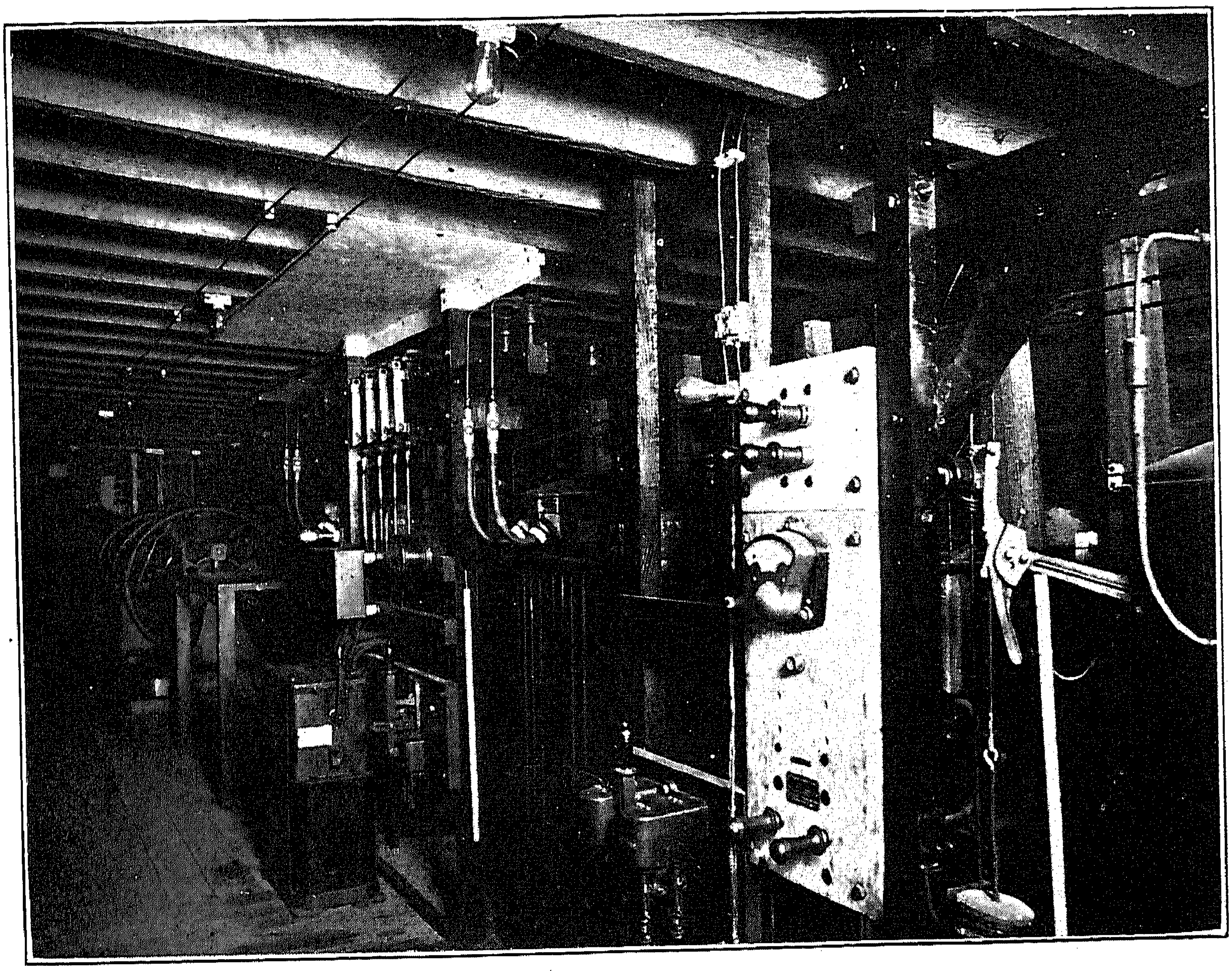

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FIG. 37—INTERIOR VIEW OF SCINTILLATOR PIER

This shows motor-generator set with station apparatus.

Fig. 38—Panoramic View from Fillmore Hill

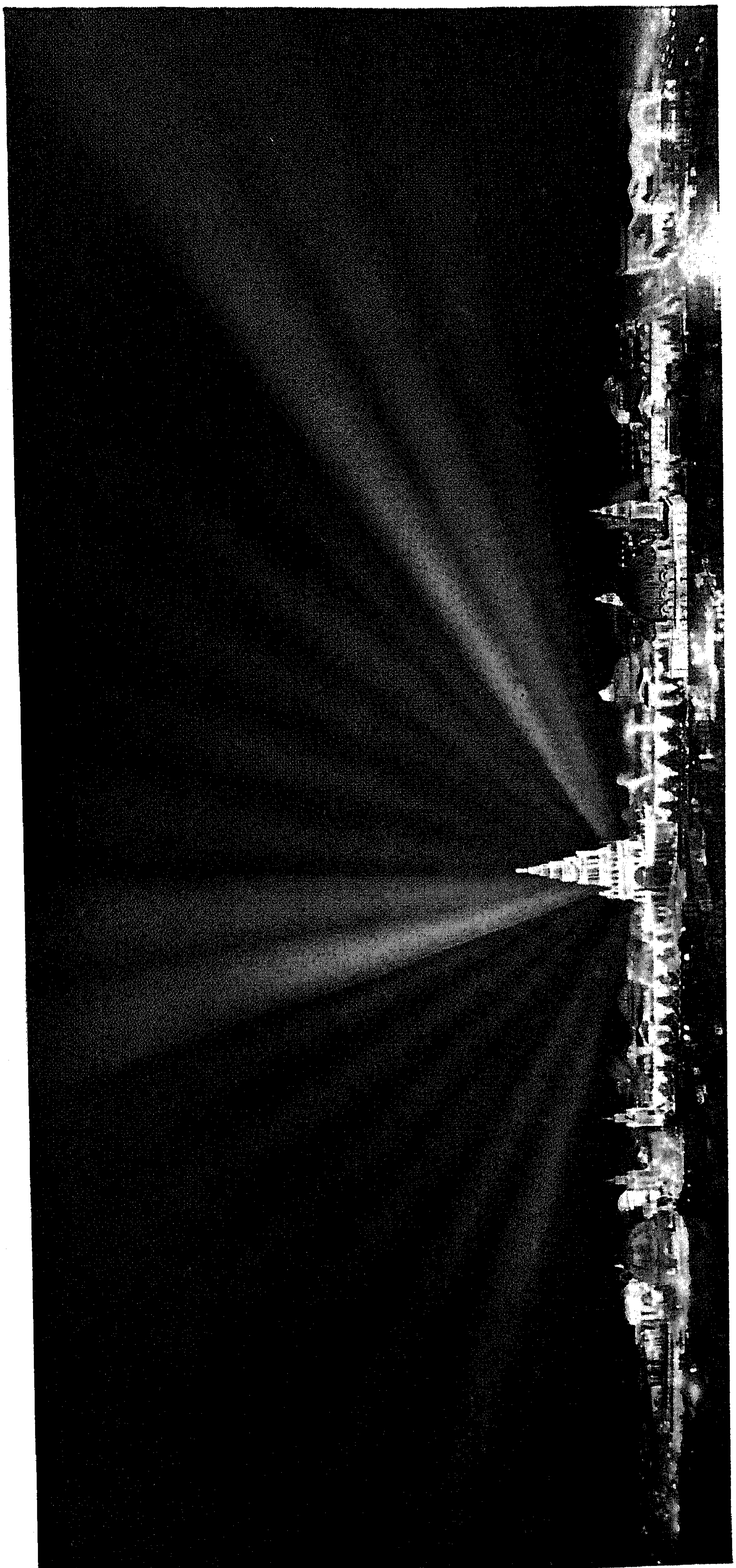


Fig. 39—Street Lighting—States and Foreign Sites

Approximately four miles of streets in this section were illuminated by 205 Penn Globe ornamental high pressure gas arcs

Fig. 40—Night View West Entrance to Zone

In addition to the concessionaires' usual outline lighting, the exposition company maintained a combination system consisting of five-light Humphrey gas arcs in ornamental lanterns and in pairs tied together by an arch of Mazda lamps with star-shaped triple reflectors supporting red ribbon festoons.

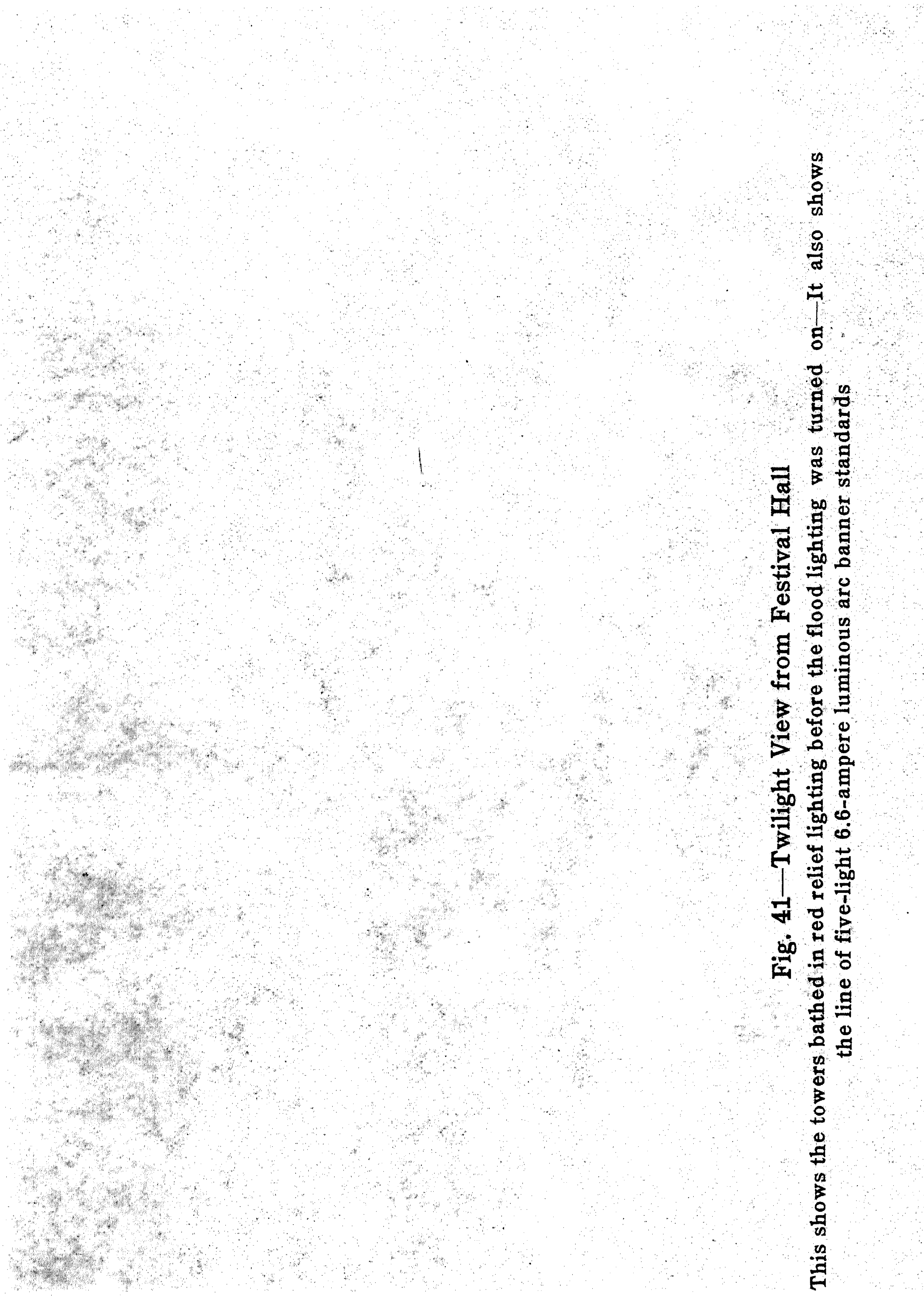


Fig. 41—Twilight View from Festival Hall

This shows the towers bathed in red relief lighting before the flood lighting was turned on—It also shows the line of five-light 6.6-ampere luminous arc banner standards

Fig. 42—Night View of Tower of Jewels and Manufacturers' Building

Illustrating the preservation of depth, or the third dimension in light by a combination of white flood light and color relief light—The scintillator and fireworks were approximately one-third of a mile in the background

Fig. 43—South Portal—Palace of Industries

Showing three-light, 35-foot Cartouche standards—This illustrates excellent depth of detail with normal shadows

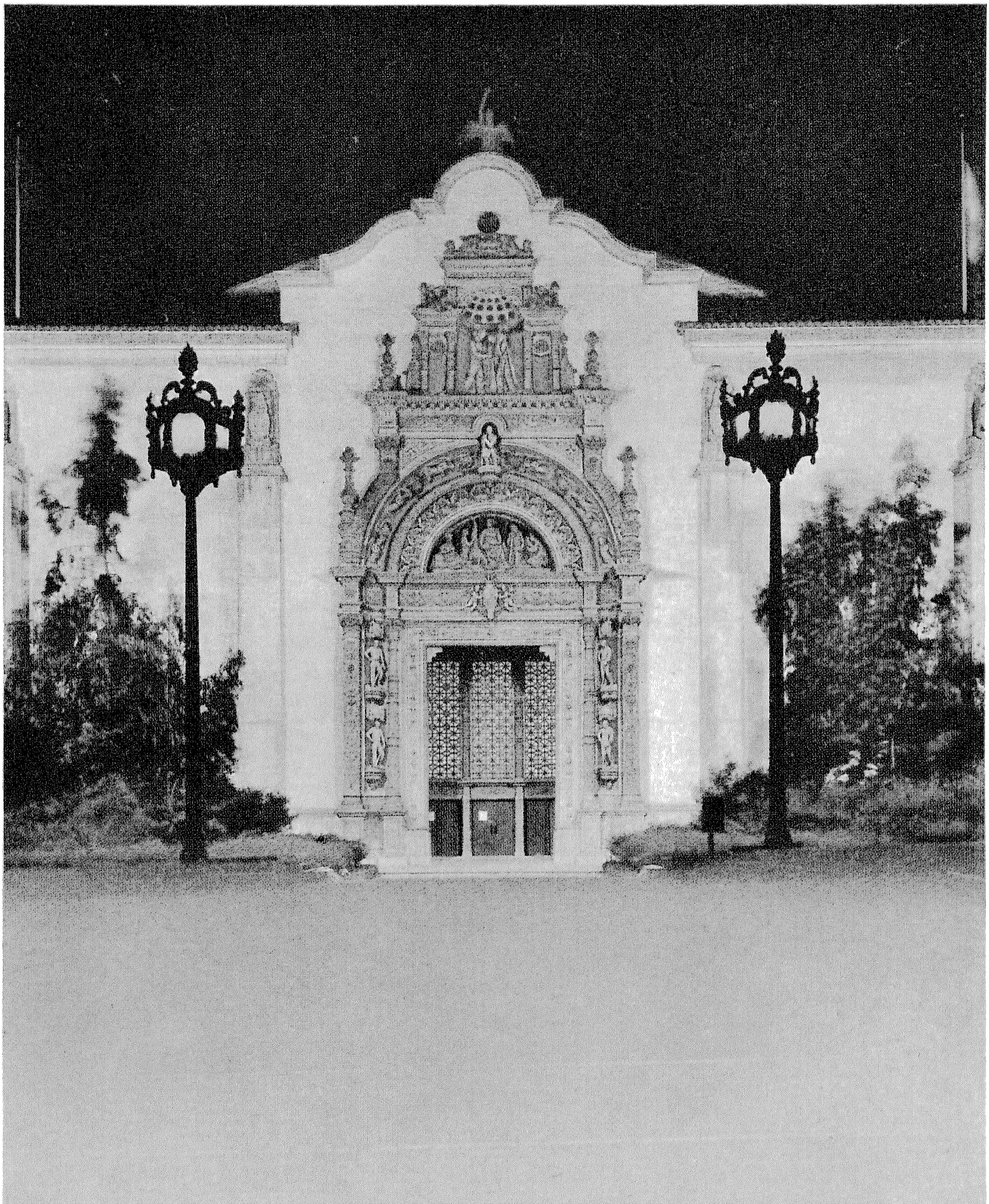


Fig. 44—Avenue of Progress from Zone Entrance

Showing the avenue flanked with three-light banner standards upon which were written the history of California and the Pacific—These in combination with the flags, which were lighted by individual arc projectors, were strongly suggestive of the carnival spirit—This made a very pleasing transition from the zone to the more artistic lighting of the main group of buildings

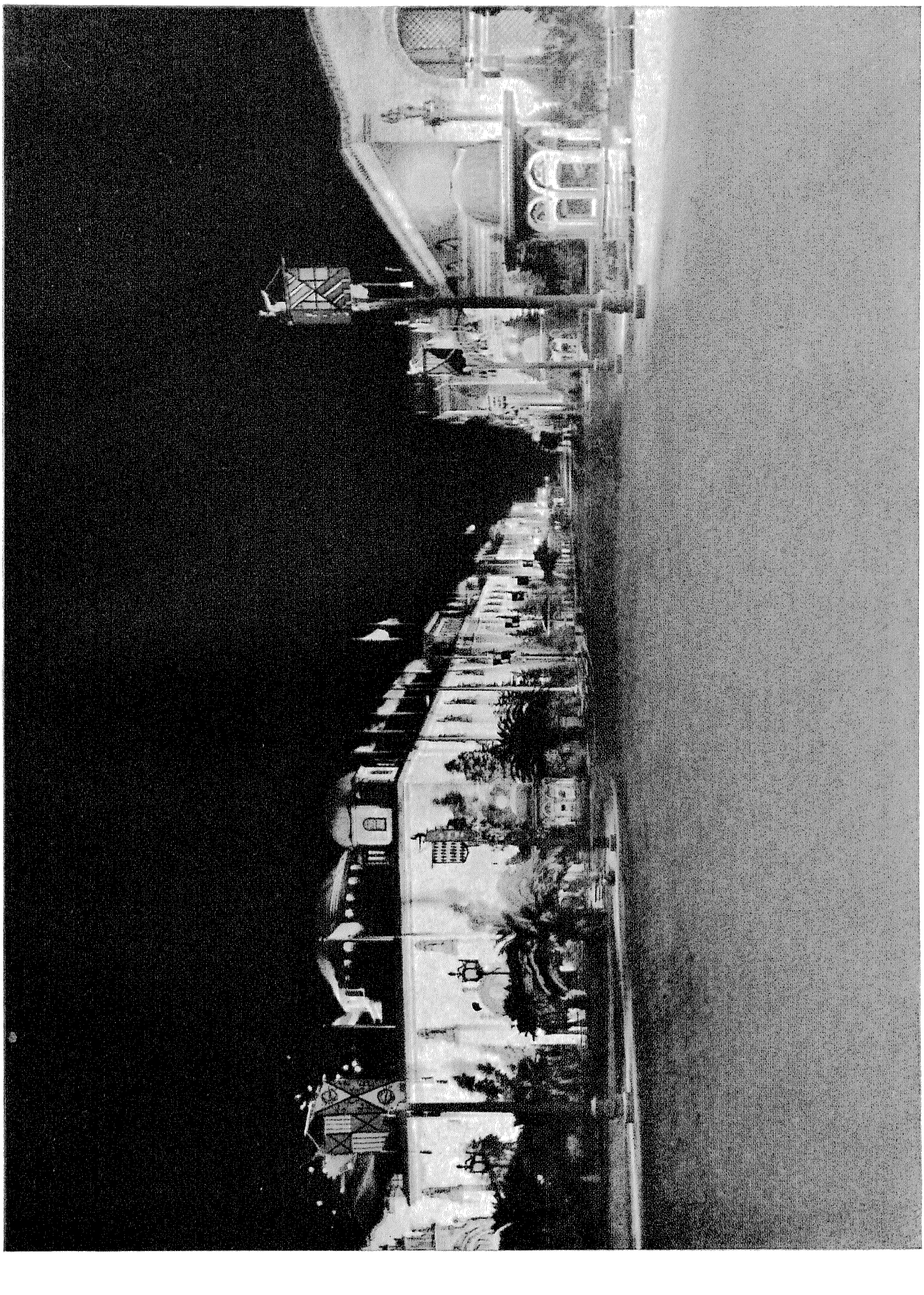


Fig. 45—A Section of Court of Abundance

Showing the organ tower and Aitken fountain, with steam caldrons and fiery serpent flambeaux—In addition to the happy effect of the orange colored cloister lanterns, the flaring gas and ruby steam caldrons and torches on the tower did much to heighten the feeling of mystery in this Court at night.

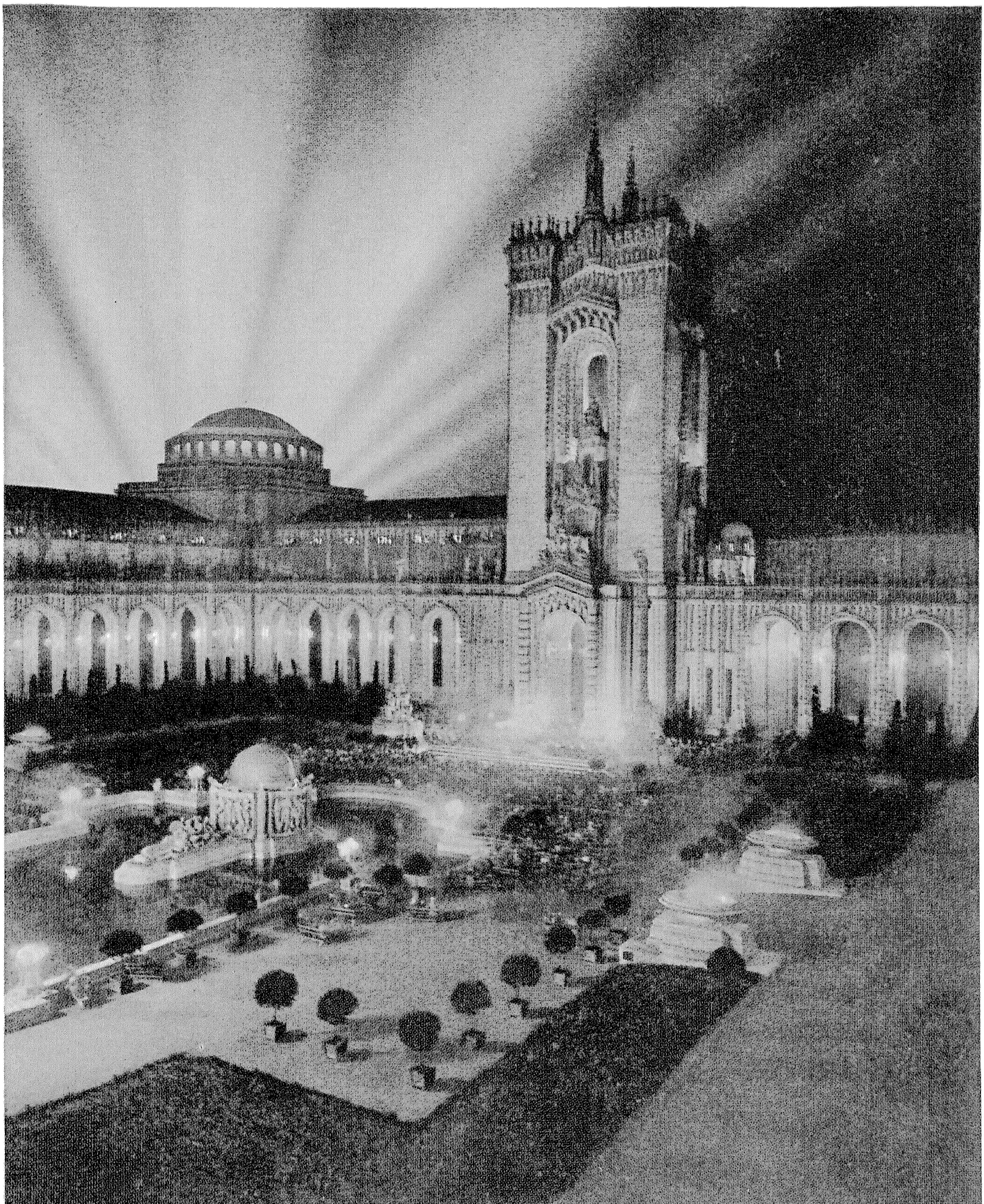
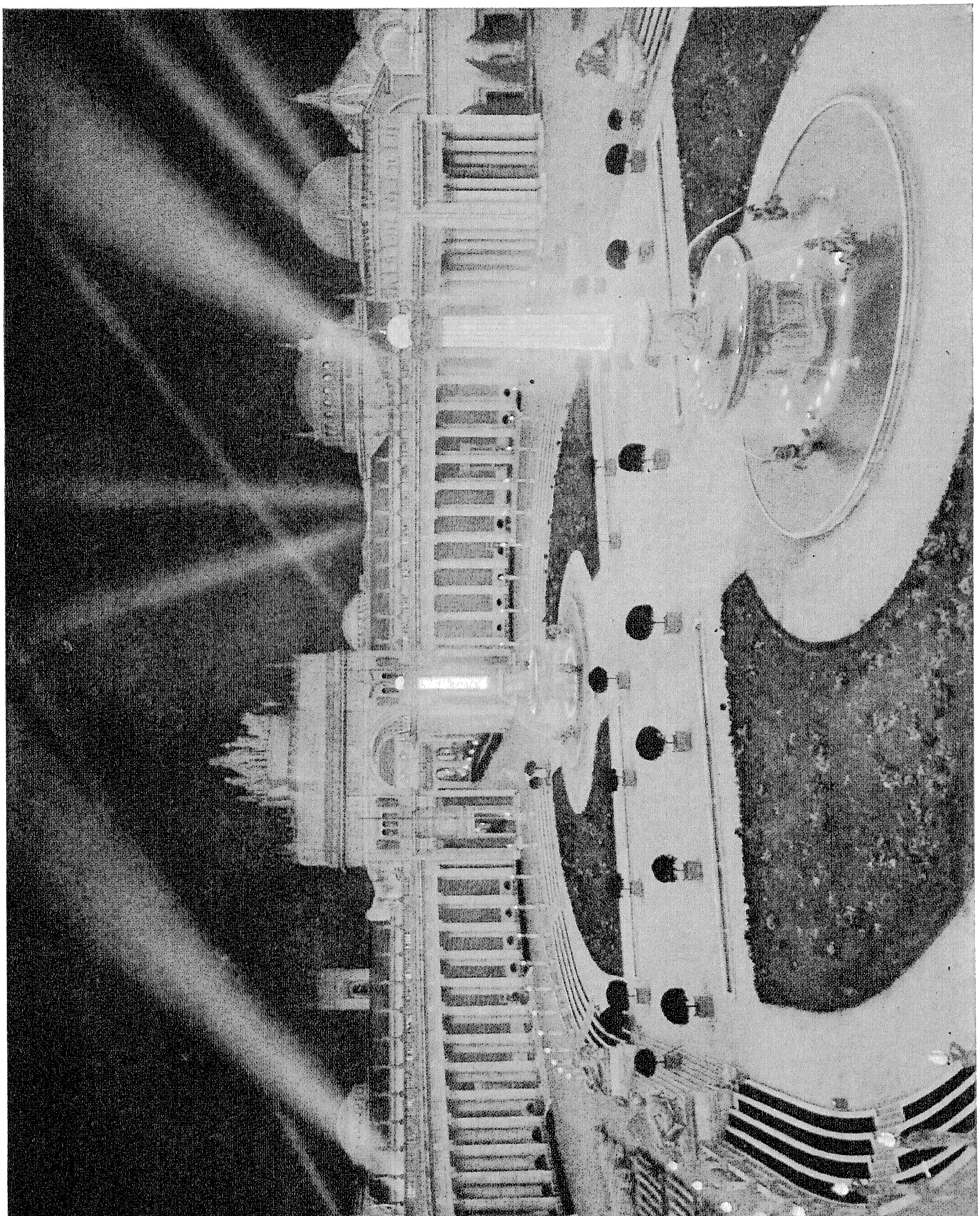


Fig. 46—Night View—Court of the Universe

This court was lighted with two 95-foot Mazda candles containing an initial candle power of approximately 500,000 and lighting an equal number of horizontal and vertical square feet—In the day time these candles lost their indentity and appeared as solid travertine columns, thereby preserving their architectural strength in effect—The lights of the Atlantes which mark the perimeter of the Sunken Gardens were for ornamental purposes only, and did not add appreciably to the surface lighting



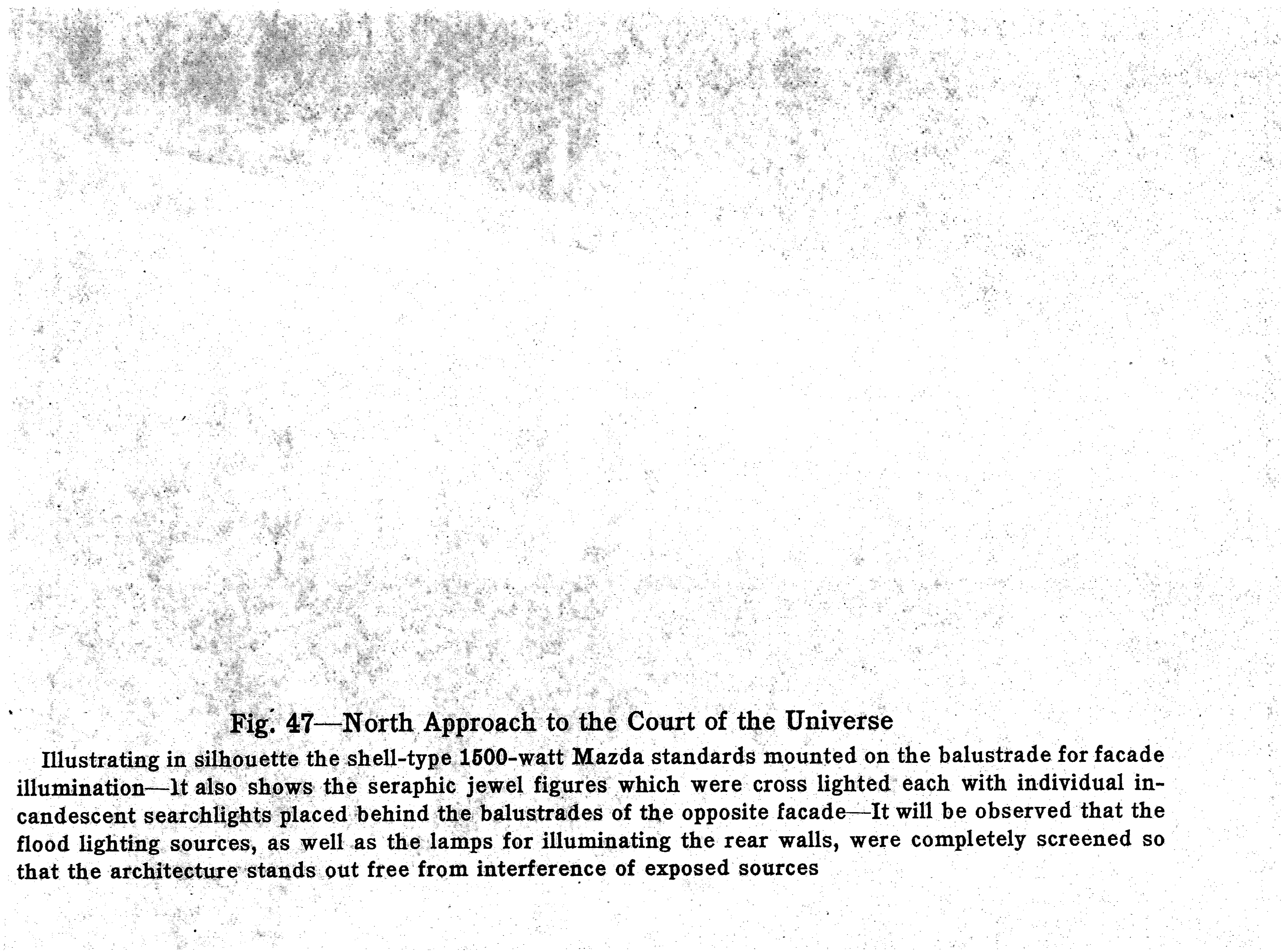


Fig. 47—North Approach to the Court of the Universe

Illustrating in silhouette the shell-type 1500-watt Mazda standards mounted on the balustrade for facade illumination—It also shows the seraphic jewel figures which were cross lighted each with individual incandescent searchlights placed behind the balustrades of the opposite facade—It will be observed that the flood lighting sources, as well as the lamps for illuminating the rear walls, were completely screened so that the architecture stands out free from interference of exposed sources

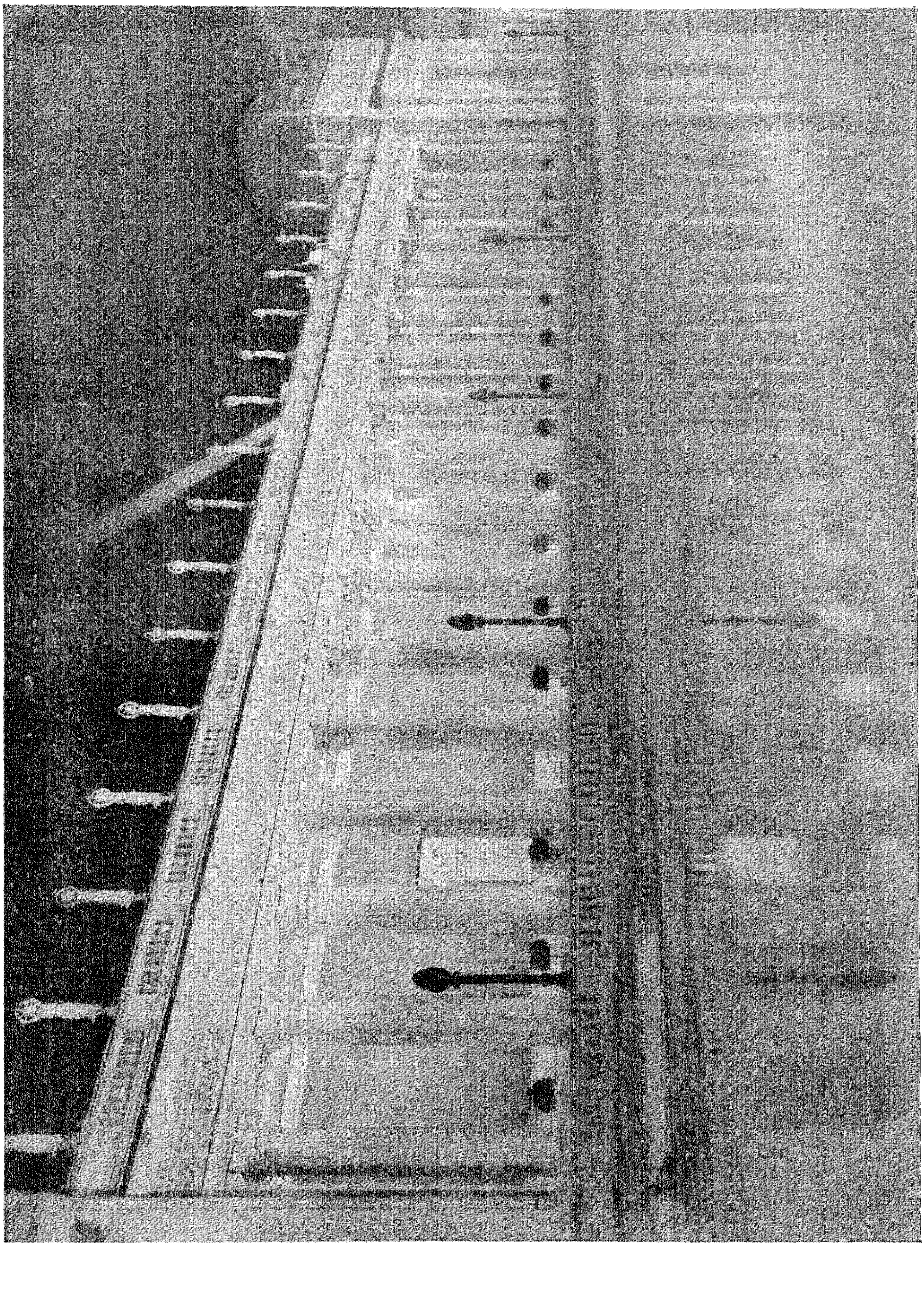
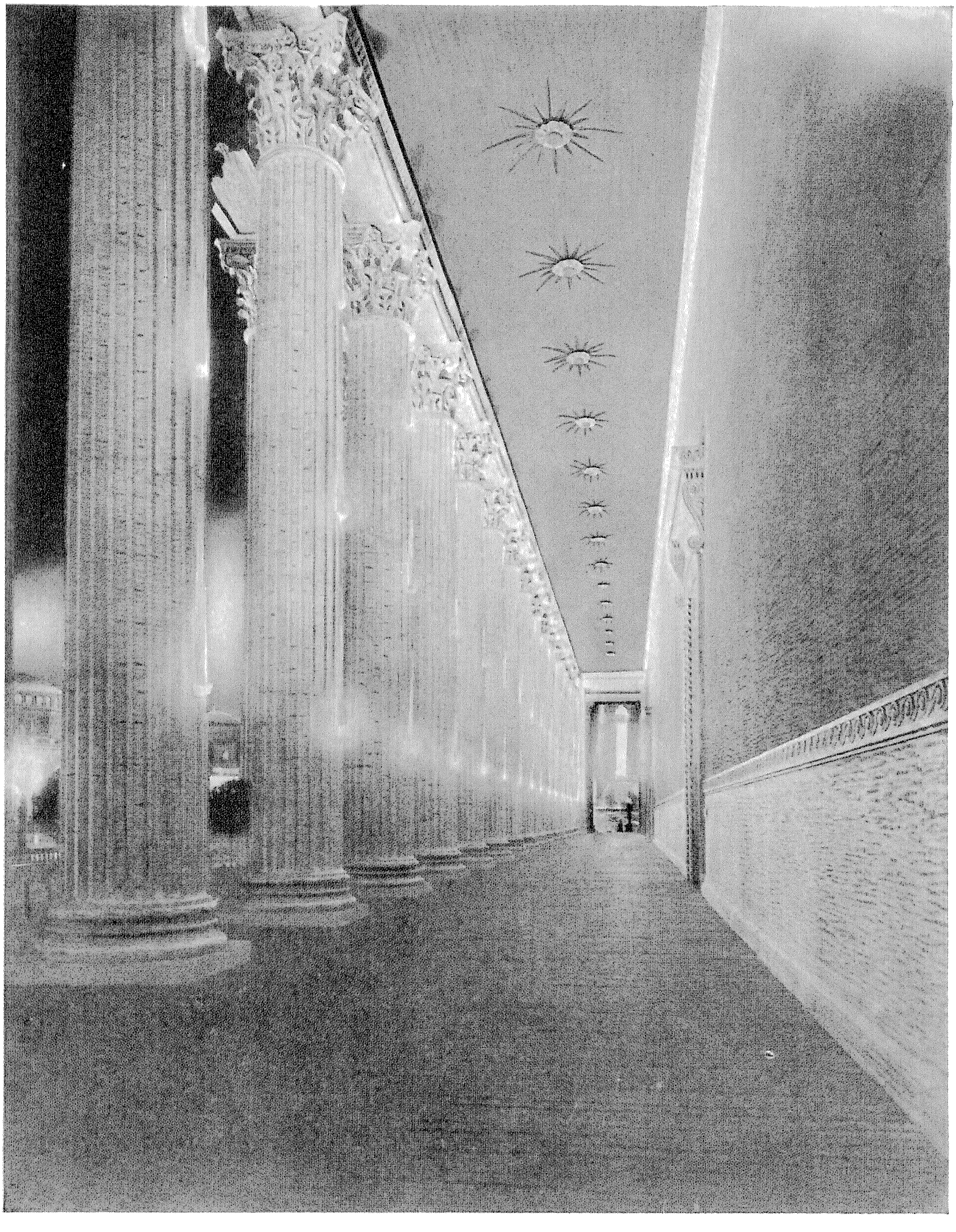


Fig. 48—Cusp Column Lights—Colonnade—Court of Universe

These lights were used for illuminating the walls and ceiling at the rear of the colonnade and they incidentally suggested a rain of fire—This method made it possible to obtain the illumination without having the source exposed to view at any position in the main court



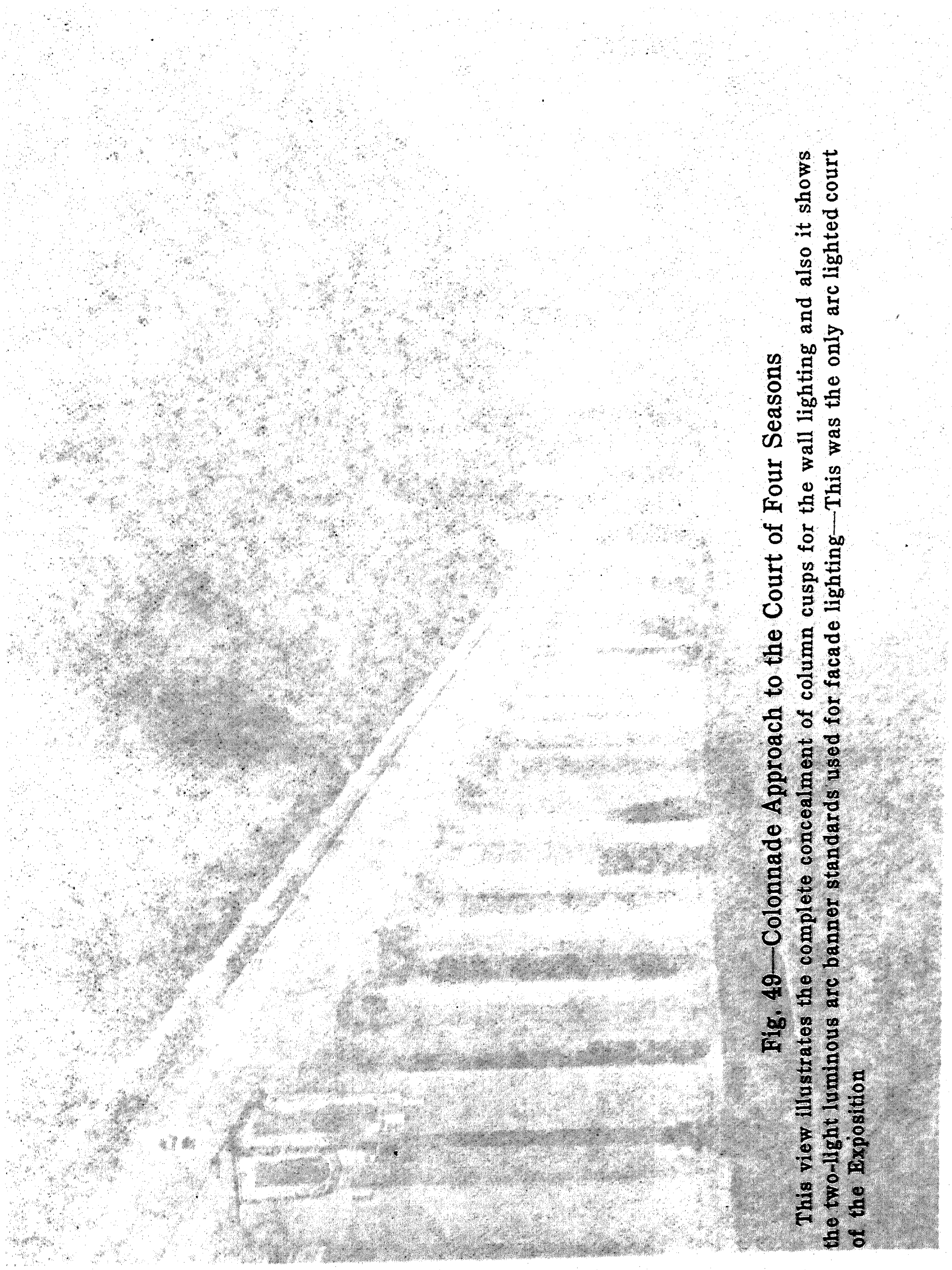


Fig. 49—Colonnade Approach to the Court of Four Seasons

This view illustrates the complete concealment of column cusps for the wall lighting and also it shows the two-light luminous arc banner standards used for facade lighting—This was the only arc lighted court of the Exposition

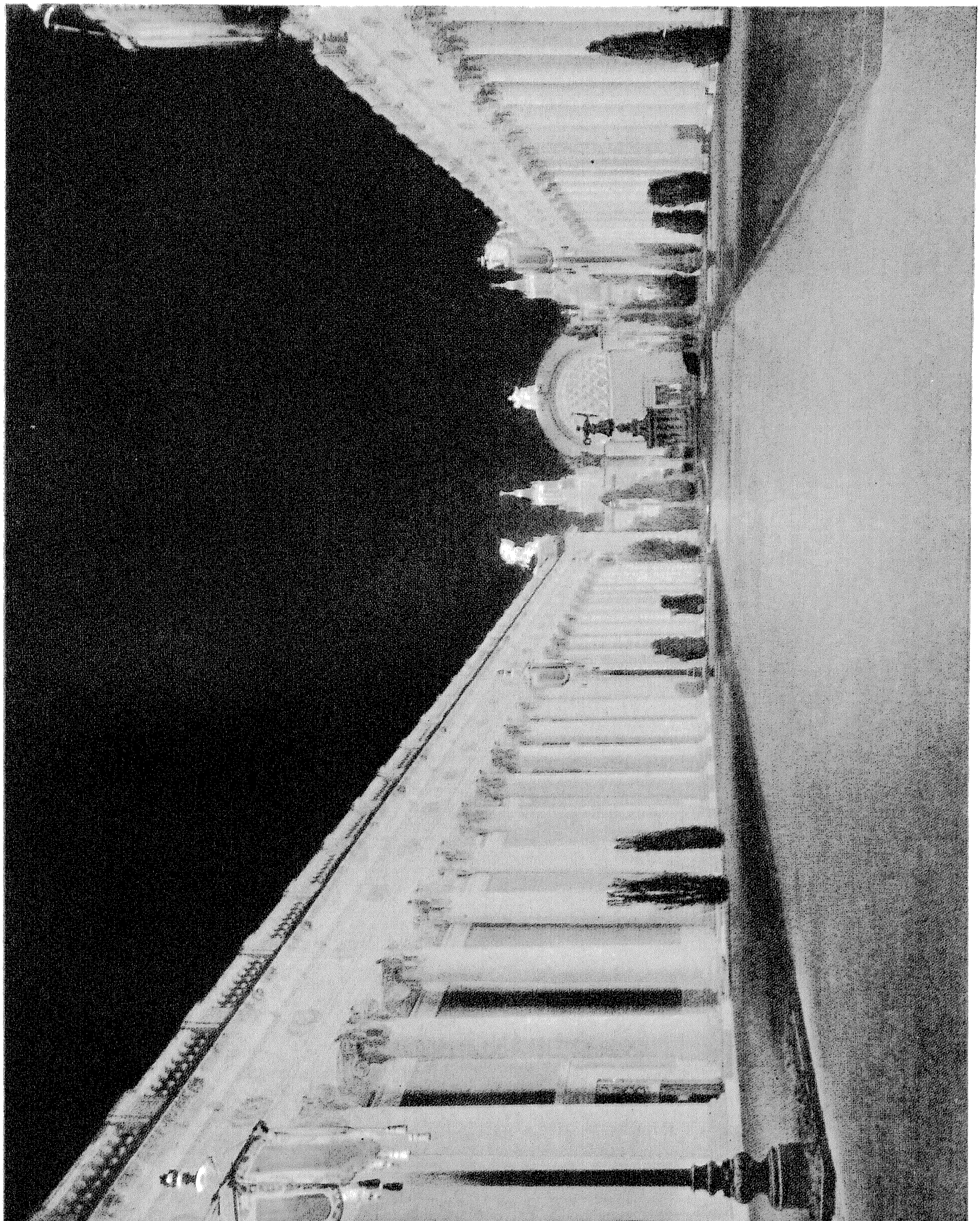


Fig. 50—Court of Four Seasons—Looking North

The circular lagoon surrounded by the dark green masses furnished some of the most beautiful reflections at the Exposition

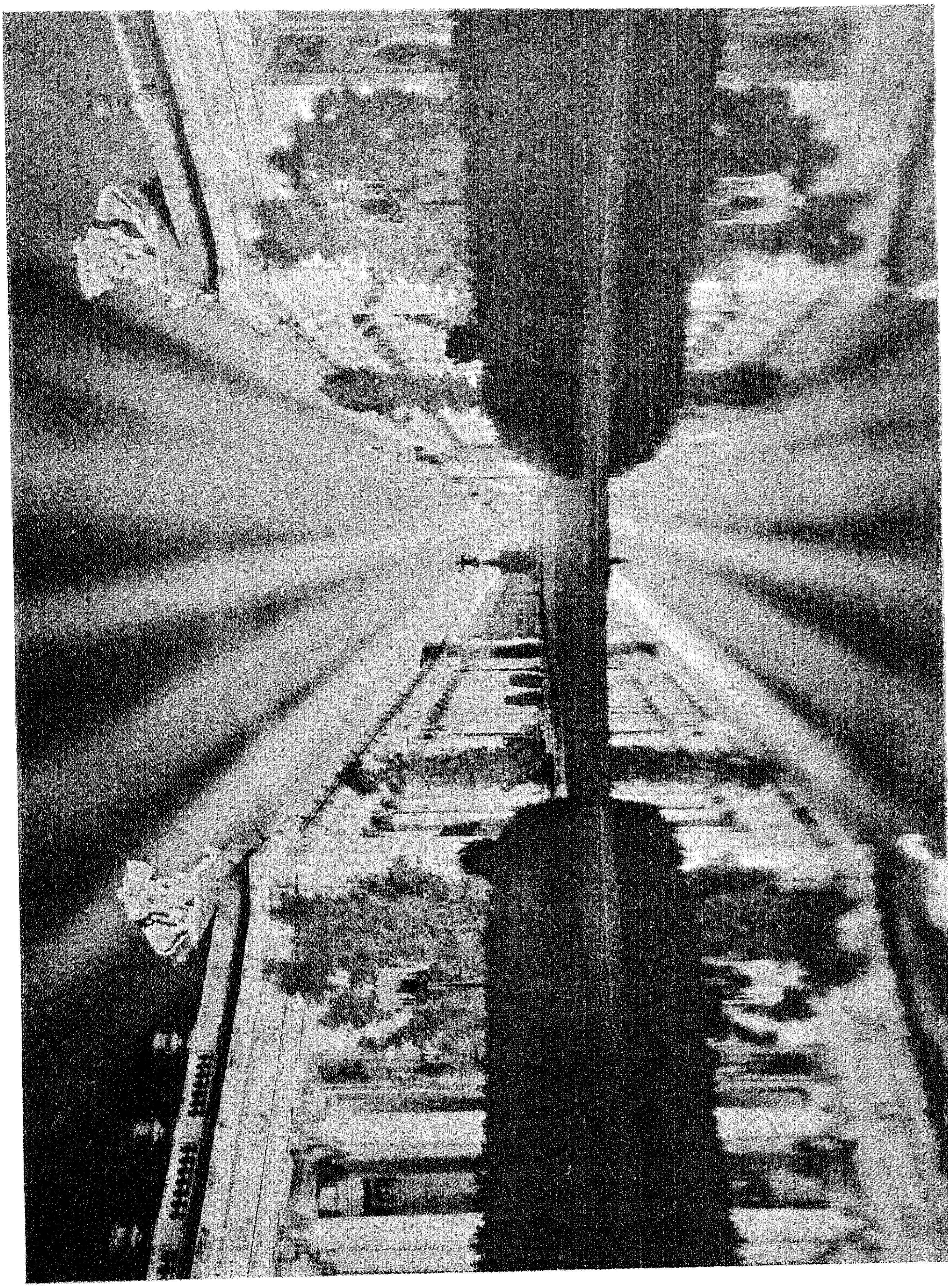


PLATE XXXIX.
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Fig. 51—West Arcade Entrance—Court of Four Seasons
This illustrates the uniformity of illumination of the facade and shows the rotunda of the Palace of Fine Arts in the distance

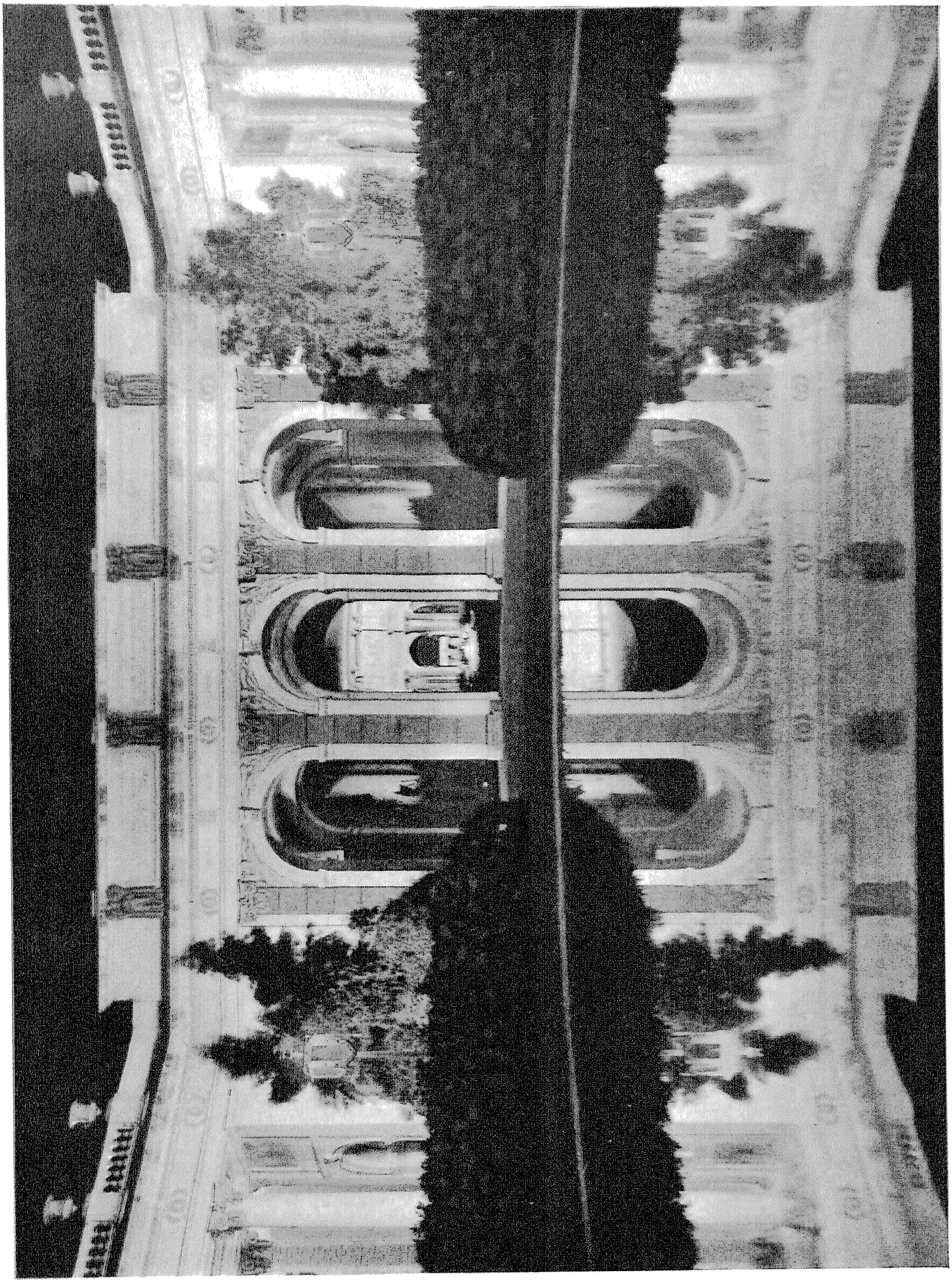


Fig. 52—Court of Palms

An excellent illustration of color harmony

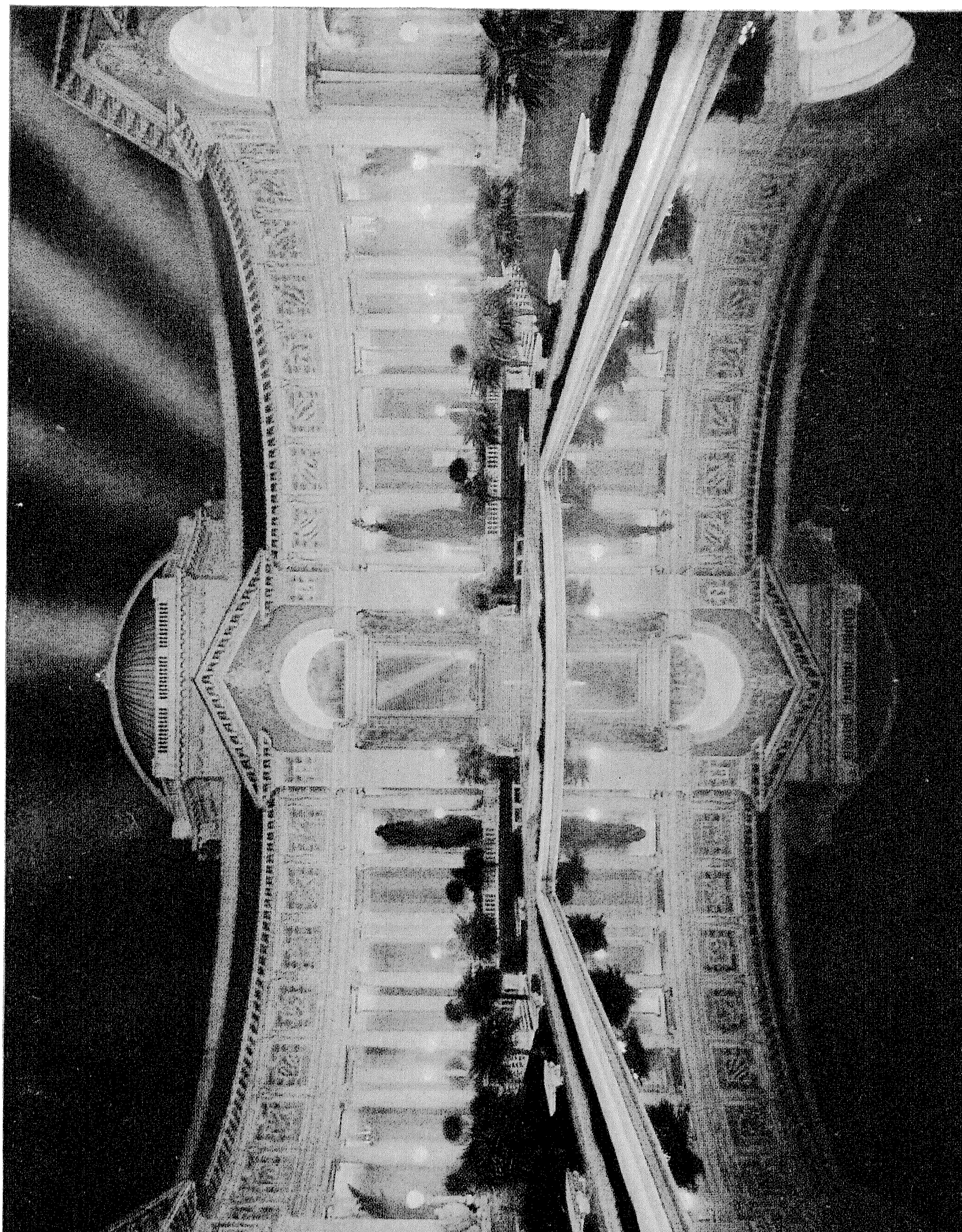
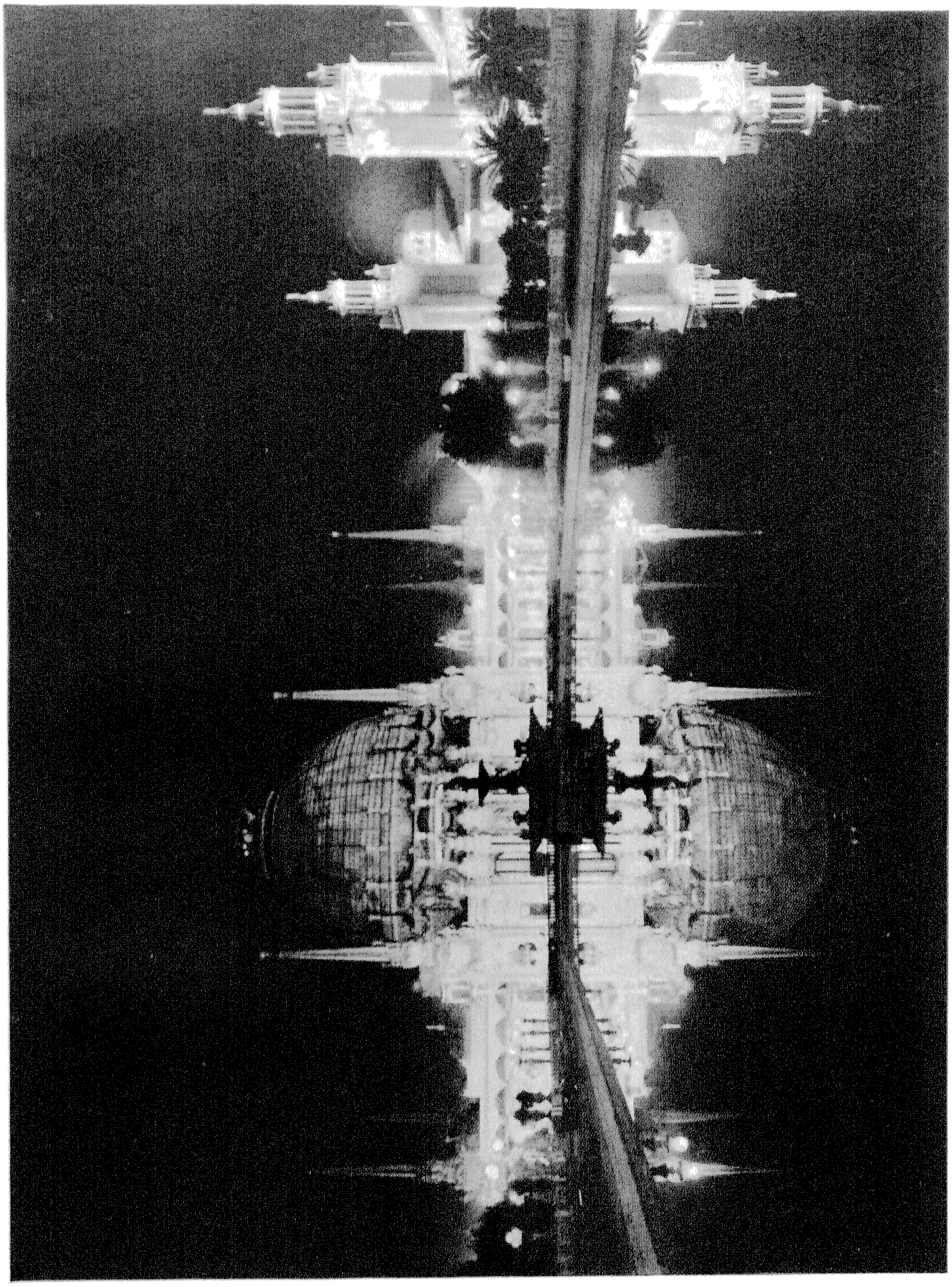


Fig. 53—Reflection in West Lagoon—South Gardens

This shows the Horticulture Building in the foreground, and the towers of the Court of Palms



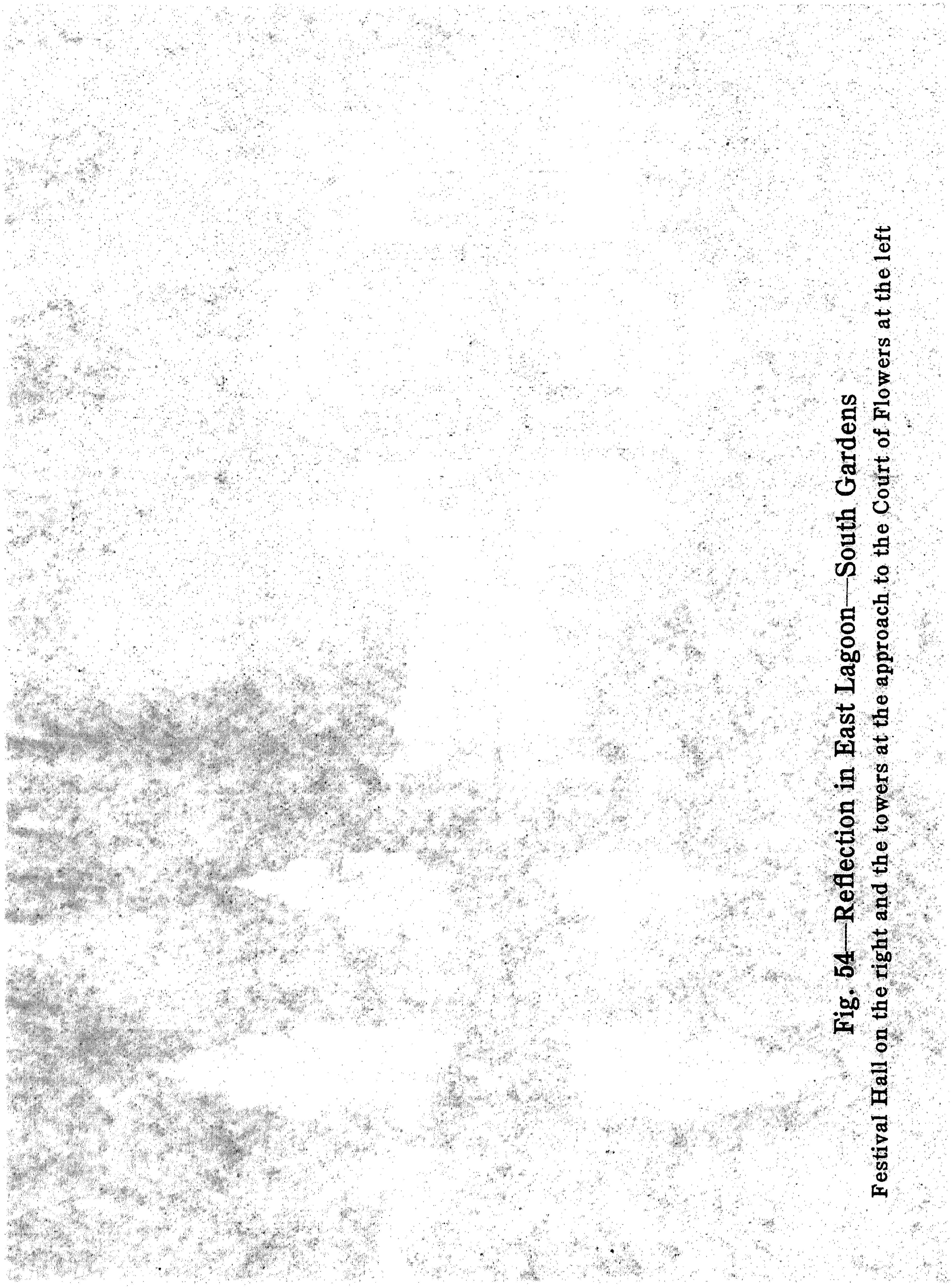


Fig. 54—Reflection in East Lagoon—South Gardens

Festival Hall on the right and the towers at the approach to the Court of Flowers at the left

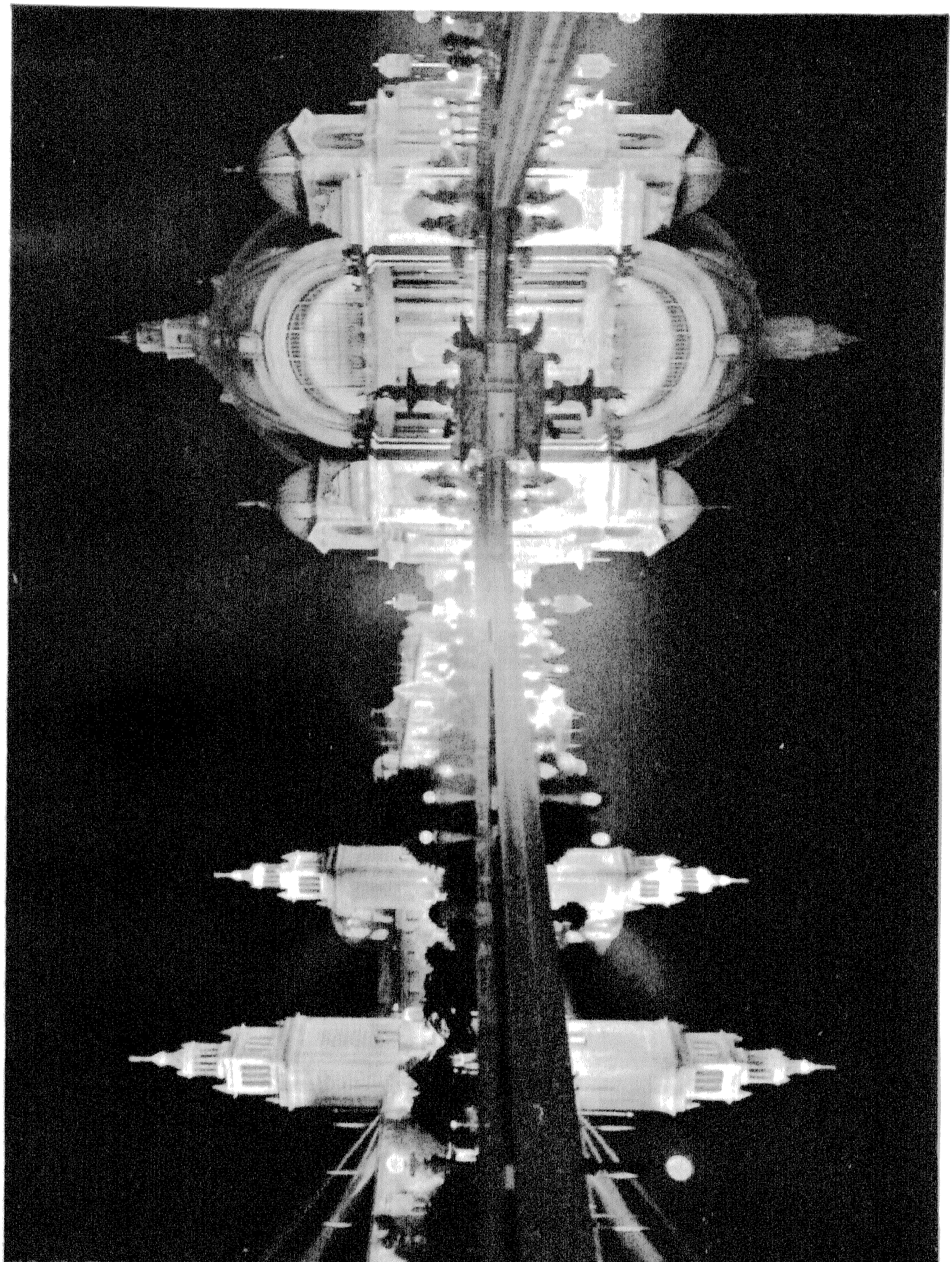


Fig. 55—Tower of Jewels

This tower was 435 feet high and was decorated with 102,000 Novagem Jewels—the tower was flood lighted with search-lights and the shadows were illuminated with rose red light

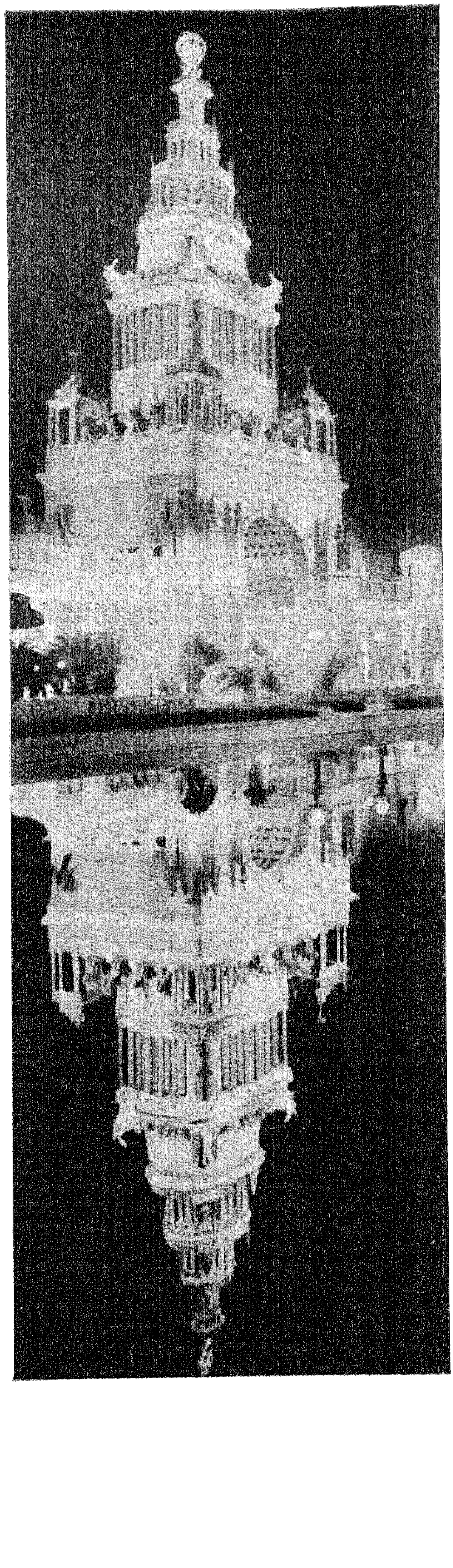


Fig. 56—West Facades of Palaces of Education and Food Products

Illuminated with 35-foot Cartouche standards, each containing three 6.6-ampere luminous arcs

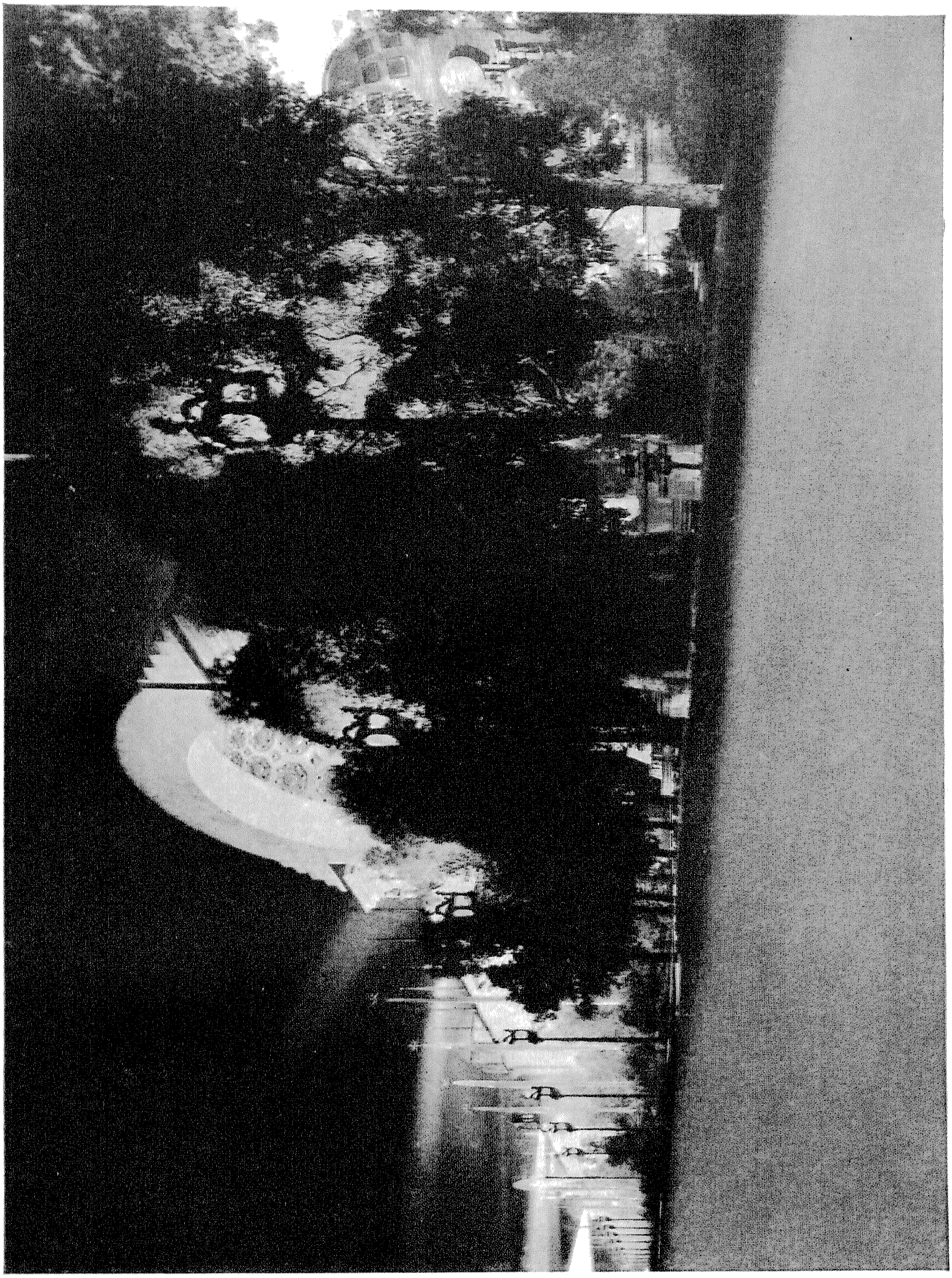


Fig. 57—Night View Under Trees—West Facade

A very striking illustration of light and shadow through the trees, and forming one of the most pleasing effects of the Exposition

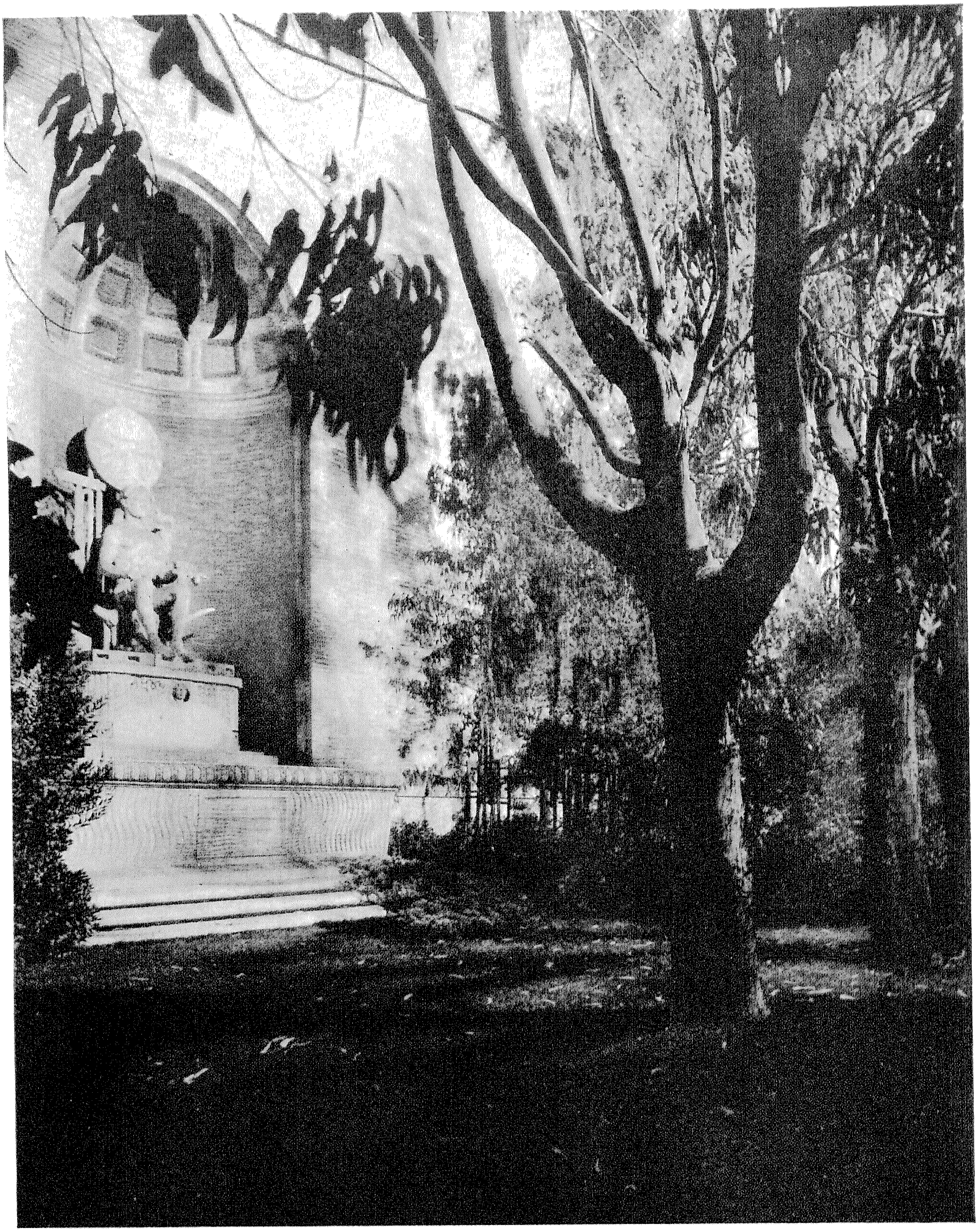


Fig. 58—Palace of Fine Arts

Showing this illuminated by search lights from the roofs of the Palaces of Education and Food Products—The interior of the rotunda and the peristyle was illuminated with Mazda lamps placed in the soffits of the colonnade cornice—Three methods of illumination were thereby provided for; flood lighting, relief lighting and a combination of both—On certain nights color was also introduced in the searchlight beams

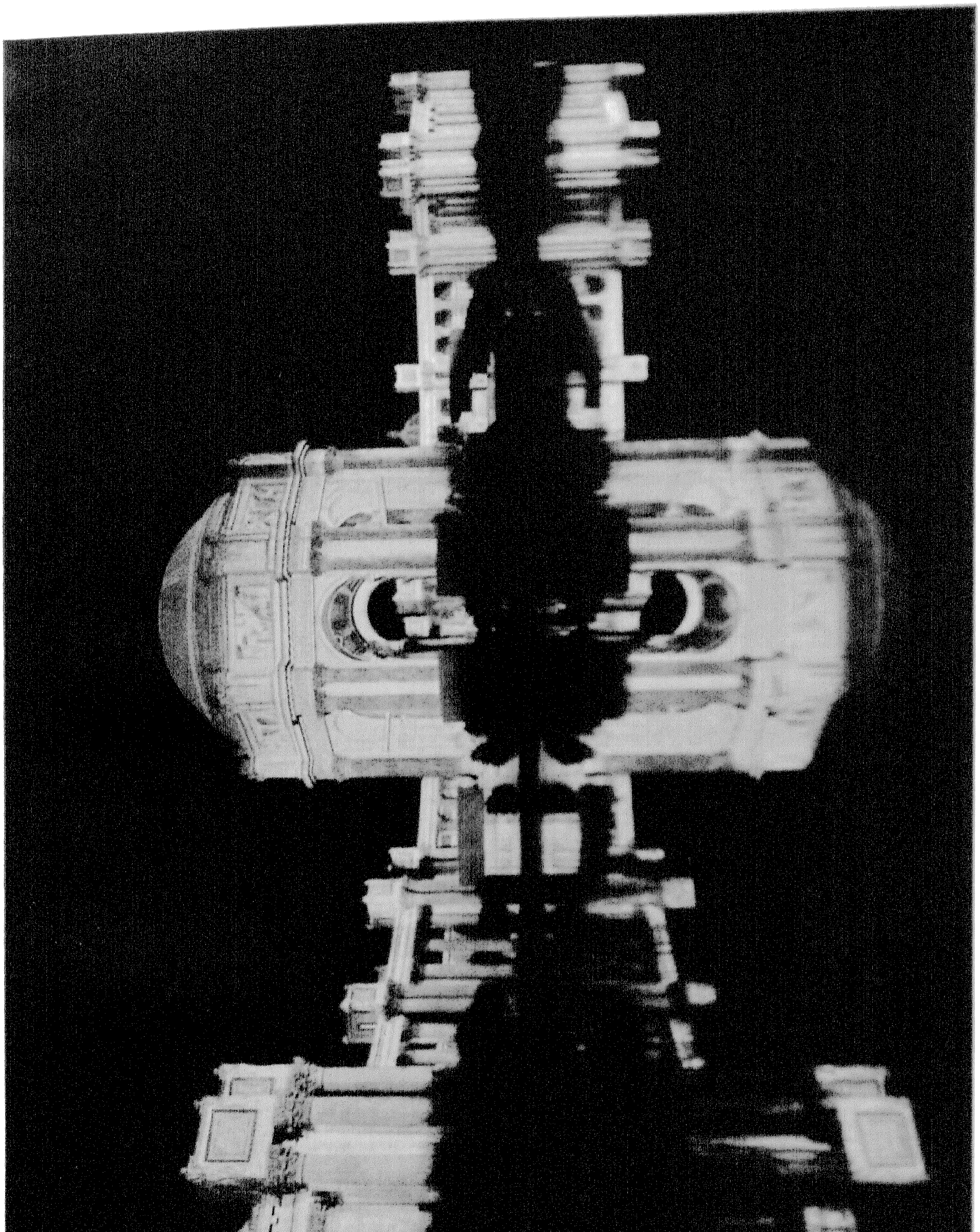
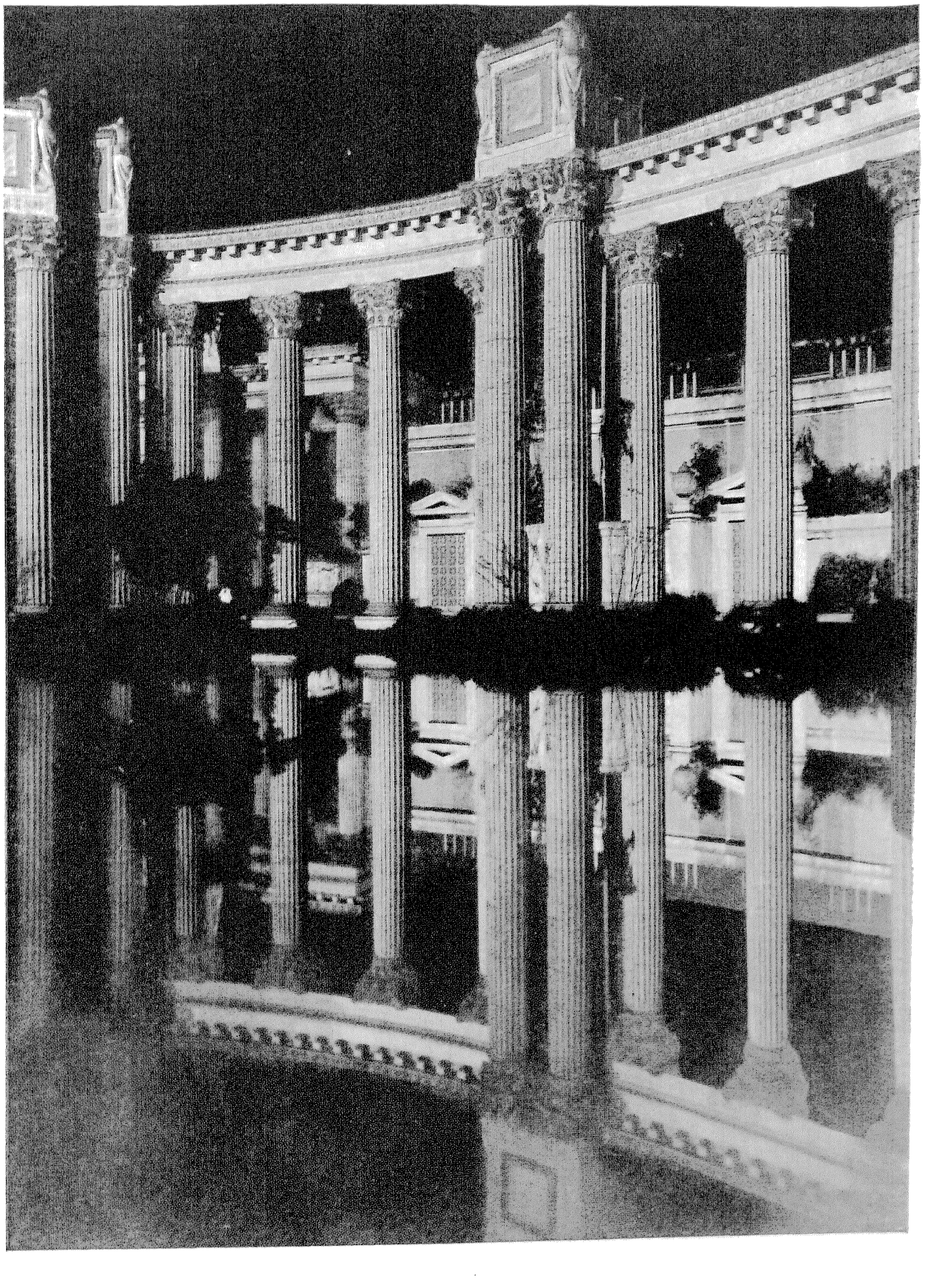


Fig 59—Peristyle Palace of Fine Arts—South Wing

A remarkable night picture

Fig. 60—Reflections of the Colonnade of the Palace of Fine Arts as Seen from the Rotunda



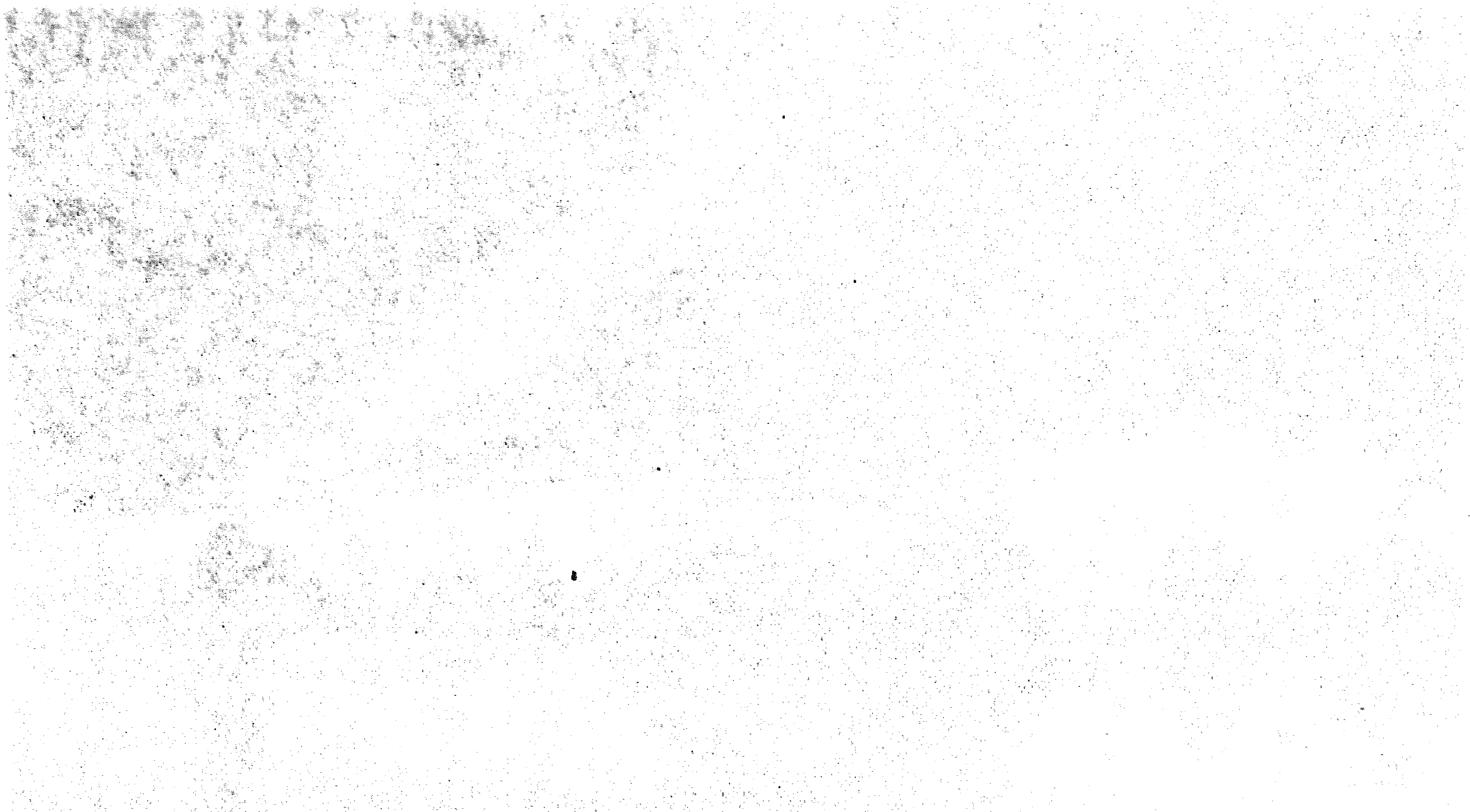


Fig. 61—West Facade Palaces of Education and Food Products as Seen from the Palace of Fine Arts

This picture was taken on a night of high fog, which accounts for the overhead brilliancy produced by the diffused white light of the scintillator

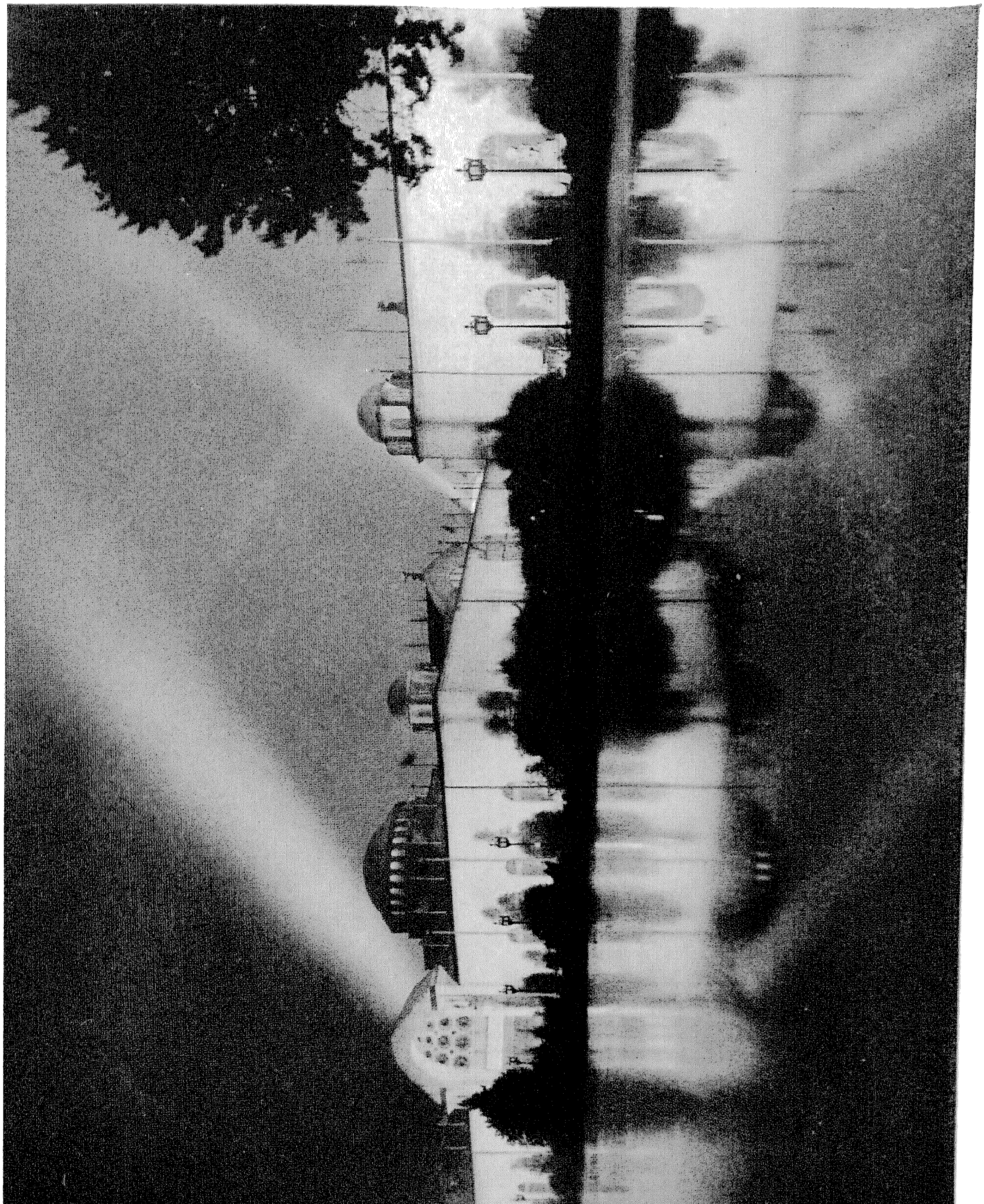


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Fig. 62—South Wing—Palace of Fine Arts

A very artistic setting and illustrating the preservation of detail in light, shadow and color under artificial light

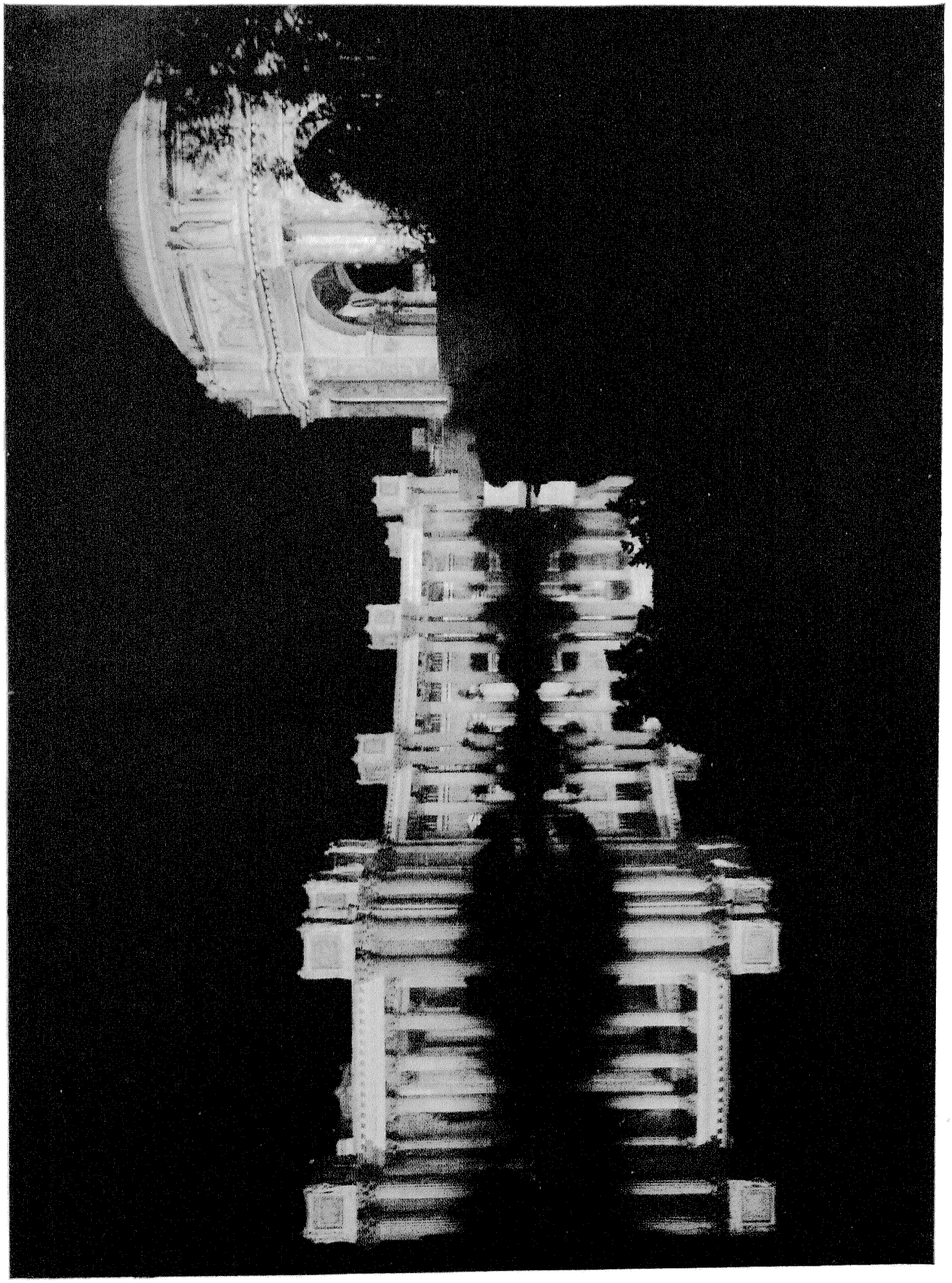
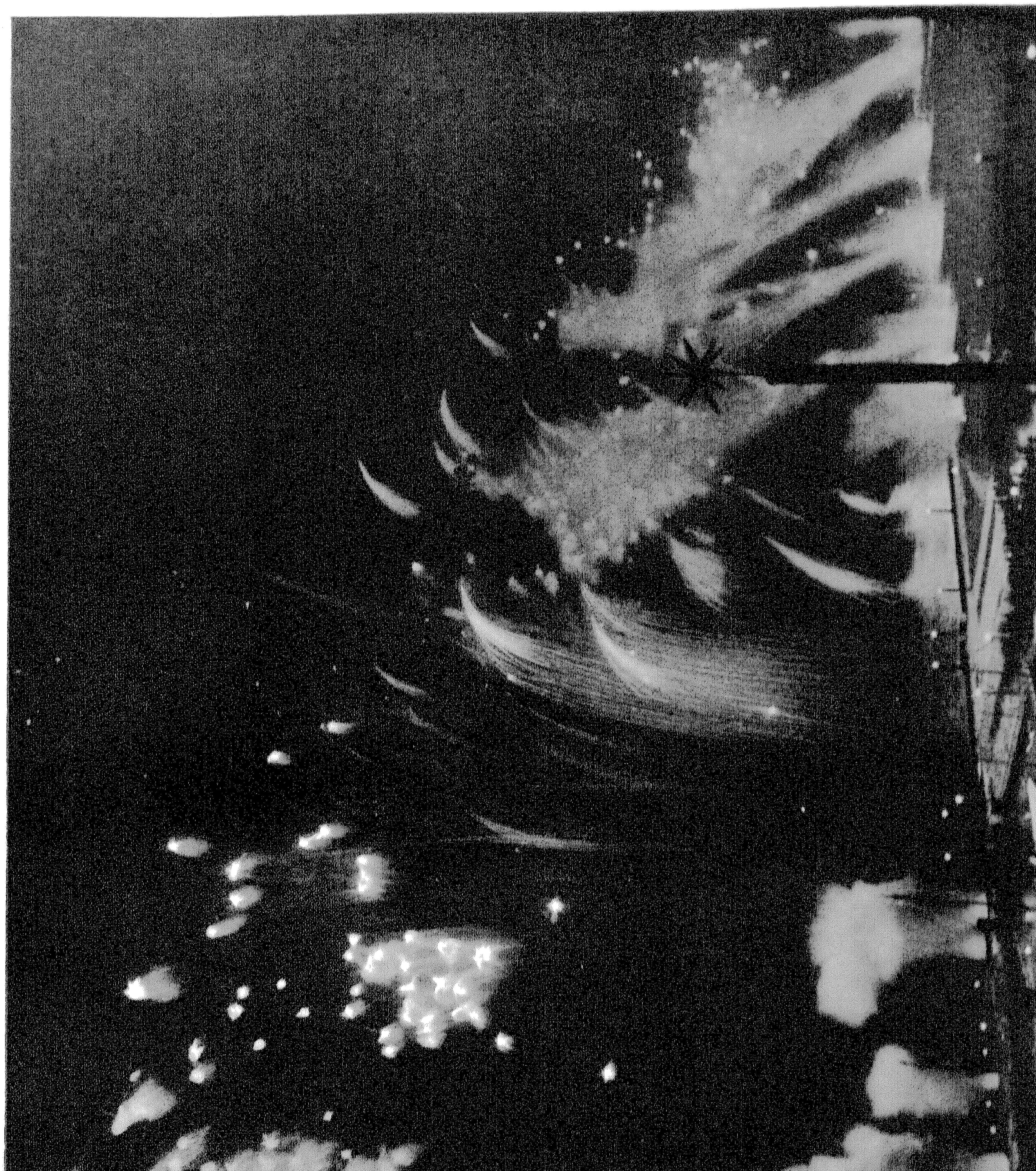


Fig. 63—The Electric-Steam-Color-Scintillator
Taken at the time of the firing of the Zone salvo

Fig. 64—The Closing Salvo, Midnight, December 4, 1915
At this instant the main lights were extinguished from the towers and the Exposition was officially closed



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